THE
ASTROPHYSICAL JOURNAL
AN INTERNATIONAL REVIEW OF SPECTROSCOPY
AND ASTRONOMICAL PHYSICS

VOLUME XXXIV JULY 1911 NUMBER 1

SOME INFRA-RED SPECTRA

By H. M. RANDALL

In 1895 Percival Lewis[1] at Johns Hopkins measured the wave-lengths of thirteen infra-red spectral lines whose wave-lengths lay between *Ca* 7664 and *Th* 11,512 Å.U., with an actual accuracy of about one Å.U.; an accuracy hitherto unattained and not equaled in the subsequent important researches of Lehmann,[2] Bergmann,[3] and Moll.[4] In two very noteworthy contributions in 1908 and 1909 Paschen[5] very materially extended the work of Lewis, attaining an accuracy in case of sources of constant intensity of a few tenths Å.U. and a maximum wave-length of approximately 28,000 Å.U. This latter limit was again extended the following year to 50,000 Å.U. by the same observer. Many of the lines found will serve as standards of wave-length in the infra-red, on account of their intensity and sharpness and the accuracy with which they were measured; while the results in general have furnished much needed data for the establishment of series laws and especially the combination principle of Ritz.

The work described in the present paper was done at Tübingen and deals with the spectra of 11 elements in the region 7500 to

[1] *Astrophysical Journal*, **2**, 1 and 106, 1895.

[2] *Annalen der Physik*, **5**, 633, 1895; **8**, 643; **9**, 246 and 1330, 1902.

[3] Dissertation, Jena, 1907.

[4] *Archives néerlandaises des sciences exactes et naturelles* (2), **13**, 100, 1908.

[5] *Annalen der Physik*, **27**, 537; **29**, 625; **33**, 717, 1910.

30,000 Å.U. Fig. 1 shows the general scheme of the arrangement. An enlarged image of the arc and carbons was thrown on the screen K by the quartz lens Q, the radiation from the carbons being intercepted by the screen, while that from the arc itself passed through the aperture, and was converged upon the slit S by means of the silvered mirrors X and Y. This slit being at the focus of the silvered mirror M, the beam came to the grating G as a parallel beam and the portion diffracted to M was brought to a focus at the thermopile P, with the aid of the plane mirror T. This approximately autocollimating arrangement is quite similar to that previously devised by Kayser and Runge,[1] and by it the advantages of an increased sharpness of definition due to smallness of the angle of incidence at the reflecting surface M is obtained. The spectrometer embodying this arrangement had been previously designed by Professor Paschen and constructed in the laboratory shops.

Fig. 2 shows a cross-section of this spectrometer somewhat more in detail. The slits, concave mirror, grating, and thermopile are

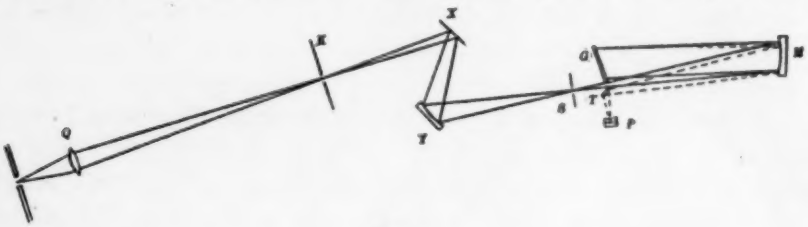


FIG. 1

all contained within a thick-walled chamber of brass, cast in a single piece with its two portions in the form of hollow cylinders. The portion containing the grating has its axis vertical and its upper end open, while the portion containing the mirror M has its axis horizontal and is open back of the mirror. The diameter of this horizontal portion is somewhat less than the height of the other portion. Besides the openings just mentioned there are openings before the slit and thermopile. The slit S is covered by a fluorite plate, and all other openings are furnished with suitable covering plates of brass with ground joints, and as the axis of the grating table passes through the bottom of the vertical chamber air tight,

[1] Kayser's *Handbuch der Spectroscopie*, 1, 635.

it is possible to use the spectrometer as a vacuum spectrometer. The graduated circle and grating table are permanently clamped together on the same axis and are turned from beneath the brass case. The circle was made by Fuess and is graduated to read directly to seconds. The entire spectrometer is held at a convenient height above the table upon suitable feet. This spectrometer, designed for special work, is much simpler in construction than are the best spectrometers which may be purchased, as these are usually designed to serve many purposes. It has been possible, therefore, to build it remarkably free from mechanical defects. In fact no

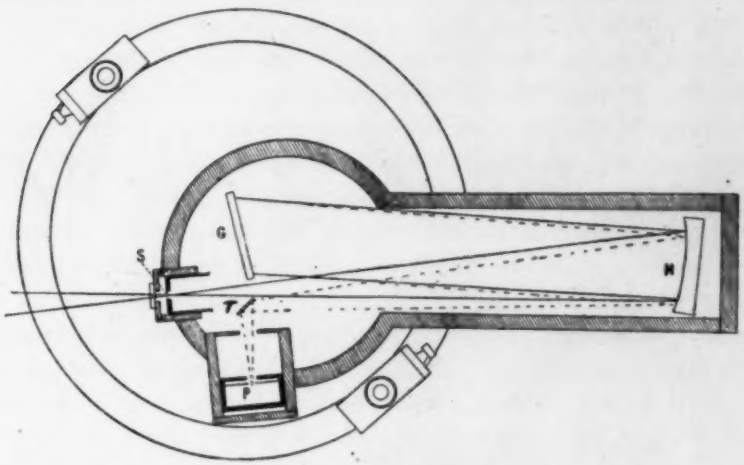


FIG. 2

variation of the zero point or spectrometer constant was noticed during the entire work, and the reading upon a line was the same whether the line was brought to the bolometer from the left or from the right. In addition to this great freedom from mechanical defects, the thick walls, with all the openings closed after the necessary adjustments had been made, prevented errors arising from rapid changes in temperature. A thermometer with the bulb within the chamber followed such slow changes as occurred with sufficient accuracy. This comparative freedom from error arising from mechanical faults or temperature effects has possibly somewhat increased the accuracy attainable, and, as a result of the

arrangement chosen (Fig. 1), the range has been extended to somewhat more than 30,000 Å.U.

The grating was a Rowland grating having 14,450 lines per inch and a ruled surface of 48 mm×35 mm. The accurately ground silvered mirror *M* was furnished by Zeiss and had an aperture of 10 cm and focal length of 35 cm. The slits were of equal width, 0.25 mm. This corresponded to about 1:25 and the thermopile therefore would cover in the first order a spectral region of about 12.5 Å.U. at 7000 Å.U., 10.5 Å.U. at 20,000 Å.U., and 6.6 Å.U. at 30,000 Å.U.

The thermopile used has very recently been fully described[1] and it will be sufficient here to say that in type it was a Rubens linear thermopile expressly adapted to the present purpose. The principal changes were a reduction of the heat capacity and conductivity of the junctions by rolling the wires to a thickness of 0.002 mm and the adoption of a method of mounting which gave a thermopile remarkably free from irregular temperature effects. As a consequence of this reduction in heat capacity the thermopile practically acquired its final temperature within two seconds after being exposed to radiation. The copper leads came out of the brass case through air-tight insulators. The resistance of the pile was approximately 12 ohms. The galvanometer was of the Paschen type.[2] It had a sensibility of about 5×10^{-11} when the period was 7.5 sec. and the resistance 16 ohms.[3] The galvanometer was adjusted to give readings proportional to the current up to deflections of 800 mm, was very steady, and, after the first adjustment, required no further attention during the year it was in use. Since the thermopile acquired its maximum temperature in approximately 2 seconds, and the half-period of the galvanometer was between 3 and 4 seconds, the first throw of the galvanometer was quite accurately proportional to the energy incident upon the pile. The copper cable, connecting the pile and galvanometer, was carefully insulated and protected against moisture and changes in temperature.

[1] F. Paschen, *Annalen der Physik*, **33**, 736, 1910.

[2] F. Paschen, *Zeitschrift für Instrumentenkunde*, **13**, 17, 1893.

[3] Scale 2.8 meters distant.

ADJUSTMENT AND CONSTANT OF SPECTROMETER

By the usual methods the spectrometer was placed in exact adjustment. The small mirror T and the thermopile were then adjusted until the image of the slit S exactly coincided with the thermopile slit and the image of a strip of foil crossing the slit S at its middle point exactly fell on the line marking the middle of the thermopile slit.

The equation $\lambda = C \sin\theta$ expresses the relation between the wave-length to be measured and the angle between the diffracted and undeviated ray. C depends upon the grating constant and the angle between the two telescopes and was determined experimentally by measuring θ for known values of λ. For this purpose the accurately determined infra-red lines[1] *Hg* 10140.58±0.2 Å.U. and *He* 10830.42±0.15 Å.U. were employed. For the first

TABLE I

Date	Temp.	λ	Angle	Constant	Constant at 17° C.
Oct. 22.....	15°.0	10140.58	16° 45′ 11″.1	35180.1	35181.4
Nov. 1.....	15.0	10140.58	16 45 9.9	0.8	2.0
Nov. 15.....	16.0	10830.42	17 55 47.3	0.4	1.0
Nov. 15.....	15.7	10830.42	17 55 47.3	0.4	1.2
Dec. 11.....	16.6	10140.58	16 45 8.5	1.5	1.7
Dec. 13.....	16.6	10140.58	16 45 8.5	1.5	1.7
					Mean 35181.5

of these lines a Heraeus quartz-glass mercury lamp with a storage battery current was used and for the second a helium tube driven by a high-potential battery was employed. With each source the intensity of the radiation was so constant that the positions of the diffracted images could be very accurately located by means of energy-curves;[2] the accuracy with such sharp lines being about 1″. In every case the positions of the images right and left were determined and half the angle between these positions taken as the value of θ. The position of the undeviated image was the mean of the readings of the right-and-left images. The values of C obtained at various temperatures were reduced to the equivalent values at

[1] F. Paschen, *Annalen der Physik*, **27**, 555, 558, 1908.

[2] *Ibid.*, p. 548.

17° C. by using 0.000018 as the temperature-coefficient of the grating. The results of this calibration are found in Table I.

This mean value, 35181.5 Å.U., has been used throughout the work.

METHOD OF MEASUREMENT

The carbons used in the lamp were the "A" grade furnished by Siemens Bros., and were especially free from impurities. In fact no trouble from this source was experienced. The upper negative carbon was about 1.5 cm in diameter and the lower positive carbon 2 cm; this latter was bored a convenient depth, the hole about 4 mm in diameter being filled with the material[1] to be examined: the metals themselves in some cases, and the fused chlorides in the others. The storage battery operated the lamp, the voltage being 64 volts and the current generally 15 to 20 amperes. An assistant, by more or less constant adjustment of the quartz lens, kept the image of the arc upon the screen *L* in such a manner that the images of the carbons fell above and below the opening through which therefore only the radiation of the arc itself went. By means of the slow-motion screw the entire spectrum, between 7500 and 30,000 Å.U. of the substance under examination, was made to pass the bolometer slit, and the spectrometer readings were taken when the galvanometer deflections indicated the presence of lines. Generally two such examinations of each spectrum were made, and it is unlikely that any lines having an intensity of 10 mm have been overlooked. The varying intensity of the arc making energy-curves unsatisfactory, the position of a line was determined by bringing the line upon the bolometer slit by turning the slow-motion screw slowly and at as uniform a rate as possible, stopping the instant the galvanometer showed its maximum deflection. The spectrometer reading was taken and the grating was then further turned in the same direction until the line had passed off the slit. The screw was then turned in the reverse direction at as nearly the same rate as before as was possible, the line being brought to the slit from the opposite side. The spectrometer reading for the maximum deflection was again noticed. Except

[1] All the substances used were furnished by Kahlbaum with the exception of the copper, where a sample of electrolytic copper was used.

for accidental variations these two readings were equidistant from the true maximum for sharp lines or for lines equally broadened on both sides. The average of a sufficient number, generally ten to twenty, of such pairs of readings therefore located accurately the position of the line. This method was found to yield the same results as the method of setting directly on the apex of the energy-curves and for the writer it proved easier and more rapid. By either method it is possible to determine the position of a sharp line whose intensity is varying more or less rapidly with an accuracy of about 5″.

In the tables which follow, the wave-lengths given are the wave-lengths in air according to the Rowland scale, while the frequencies are the reciprocals of the wave-lengths reduced to corresponding values *in vacuo*. The tables contain all the measurements which have been made and in every case great care has been taken that the lists of lines given contain no higher orders of lines of shorter wave-lengths. The intensities of the lines are but roughly estimated by means of the galvanometer deflections which occurred when a moderate amount of material was in the arc, the current being 15 amperes for silver and copper and 20 for the remaining materials. When the lines were sufficiently intense and sharp to permit measurements in higher orders, the determinations in the different orders have been indicated. No mean value[1] is thought to be in error by an amount greater than the quantity preceded by the plus and minus sign; however, should any of the lines be broadened on one side only, the measurements may be in error by greater amounts. As an inspection of the results will show, these possible errors do not involve simply the accidental errors of observation. They embrace in fact all instrumental errors as well, and are arrived at largely by considering the accuracy with which the stronger visible lines can be measured in the second- and third-order spectra.

With the exception of a number of lines in barium and a single line in strontium, all the infra-red lines of the first six elements have

[1] In a few instances the values of the wave-lengths here given vary slightly from those given in the preliminary paper (*Annalen der Physik*, **33**, 739, 1910); this is due in general to the fact that subsequent measurements have been incorporated with the earlier ones.

found places in the regular series or in Ritz combination series. Immediately following the tables of results, those series are given which contain the new infra-red lines as members and which at the same time furnish the terms from which the combination series are obtained. Only so many terms of these series are given as are necessary for this purpose. The wave-lengths are in general those of Kayser and Runge and Saunders, while the limits are those of Ritz.

COPPER

It was found that a bead of copper about 5 mm in diameter in a shallow cavity of the positive carbon gave the steadiest and most intense radiation, 15 amperes being the most suitable current. The entire spectrum in the region 7000 to 30,000 Å.U. was twice carefully examined.

Intensity	130	6	250	15	6	60
Order..	I	II	I	II	III	I
λ.....	7935.2		8093.4		8093.3	16009.3
	5.0		4.2	8093.4	3.4	7.4
	5.1	7934.1	3.9	3.1	3.6	8.8
	4.6	3.8				8.5
Mean λ	7935.0	7934.0±0.5	8093.8	8093.3	8093.4±0.5	16008.5±1.0
ν.....		12600.5			12352.2	6245.00

Intensity.....	12*	10*	6
λ.....	16654.9	18194.8	18229.7
	2.0	4.5	9.5
			9.3
Mean.....	16653.4±2.5	18194.7±3.0	18229.5±0.5
ν.....	6003.16	5494.63	5484.14

7934.0	$2\,p_2-2.5\,s$			Subordinate series II
8093.4	$2\,p_1-2.5\,s$			Subordinate series II
16008.5	$2.5\,s-3\,p_1$	16004.9 Comp.	$3\,p_1=12924.8$	Combinations according to Ritz
16653.4	$3\,p_1-4\,d'$	16650.8 Comp.		
18194.7	$3\,d'-4\,\Delta p$	18199.8 Comp.	$4\,\Delta p=6879.1$†	Bergmann series
18229.5	$3\,d\ -4\,\Delta p$	18221.3 Comp.		

* These lines were found only when currents greater than 20 amperes were used.

† The value of $4\Delta p$ obtained from the line 2369.97 is used as this line is more accurately measured than any of the other lines from which it may be obtained.

The following lines in the visible spectrum are combination lines.

4015.8	$2p_2-4\Delta p$*	$4\Delta p$ 6876.9
4056.8	$2p_1-4\Delta p$*	$4\Delta p$ 6880.0
3652.56	$2p_2-5\Delta p$	$5\Delta p$ 4401.4
3512.19	$2p_1-6\Delta p$	$6\Delta p$ 3059.1

*Ritz, *Physikalische Zeitschrift*, 9, 527, 1908.

The very strong pair, 5782.30 and 5700.39, may be represented as $x-2p_i$ which makes $x=49061.2$. The following lines are combinations in which this term appears.

2766.50	$x-3p_1$	$3p_1$	=12924.8
2768.94	$x-3p_2$	$3p_2$	=12956.6
2369.97	$x-4\Delta p$	$4\Delta p$	= 6879.1
2238.52	$x-5\Delta p$	$5\Delta p$	= 4402.4
2724.04	$x-3d$	Comp.	= 2724.35

The principal series lies in the ultra-violet and the terms $M=3$ may be computed from the values of $3p_1$ and $3p_2$ obtained above.

	$M=2$	$M=3$	
λ	3247.65	2024.42 Comp.	Observed by Kayser and Runge 2025.1±0.2
ν	30782.9	49381.4	
Mp_1	31523.3	12924.8	
λ	3274.06	2025.73 Comp.	
ν	30534.5	49349.6	
Mp_2	31771.8	12956.6	

SUBORDINATE SERIES II

$2p_2=31771.8$			
M	1.5	2.5	3.5
λ	3274.06	7934.0	4480.59
ν	30534.5	12600.5	22312.3
Ms	62306.3	19171.3	9459.5
$2p_1=31523.3$			
λ	3247.65	8093.4	4531.04
ν	30782.9	12352.2	22063.9
Ms	62306.2	19171.1	9459.4

SUBORDINATE SERIES I

$2p_1=31523.3$			
M	3	4	5
λ	5218.45	4062.94	3688.6
ν	19157.6	24605.8	27103.0
Md	12365.7	6917.5	4420.3
λ	5220.25	4063.50	
ν	19151.0	24602.6	
Md'	12372.3	6920.7	
$2p_2=31771.8$			
λ	5153.33	4022.83	3654.6
ν	19399.7	24851.2	27355.1
Md'	12372.1	6920.6	4416.7

SILVER

The metallic silver was fed into the arc until the hole in the lower carbon, about 5 cm deep, was filled. With a current of 15 amperes the arc burned satisfactorily until the silver was nearly used up. The spectrum was twice examined to 30,000 Å.U.

Int....	200	30	10	250	40	10	10*
Order..	I	II	III	I	II	III	
	7688.9	7687.6	7688.1	8273.9		8274.2	
	8.8	8.2	8.6	4.2		4.0	
	9.0	8.5	7.9	4.3	8274.2	4.0	12551.0
Mean....	7688.9	7688.1	7688.2±0.5	8274.1	8274.2	8274.1±0.5	12551.0±5.0
ν.....			13003.4			12082.6	7965.33
Int.....		60		20		15*	15
		16819.0		17416.6			18381.3
		9.5		5.1		18307.1	2.1
		8.9		5.3		8.7	2.6
Mean.....		16819.1±0.8		17415.7±1.0		18307.9±3.0	18382.0±1.0
ν.....		5944.09		5740.40		5460.66	5438.65

Previous determinations—Lewis:† 7688.4, 8274.02

* Found only when the current was over 20 amperes.

† *Astrophysical Journal*, 2, 1 and 106, 1895.

7688.2.....	$2p_2-2.5s$		Subordinate series II
8274.1.....	$2p_1-2.5s$		Subordinate series II
12551.0.....	$3d'-5\Delta p$	$5\Delta p=4384.7$	Bergmann series
18307.9.....	$3d'-4\Delta p$	$4\Delta p=6889.3$	Bergmann series
18382.0.....	$3d-4\Delta p$	$4\Delta p=6891.0$	Bergmann series
16819.1.....	$3p_1-2.5s$	16819.8 Computed	Ritz combination
17415.7.....	$3p_2-2.5s$	17414.2 Computed	Ritz combination

The values of $3p_1=12594.1$ and $3p_2=12797.0$ are obtained from the following combinations of Ritz:

5276.4.....	$2p_2-3p_1$	$3p_1=12593.8$
5545.86.....	$2p_1-3p_1$	$=12594.2$
5333.5.....	$2p_2-3p_2$	$3p_2=12797.0$

The principal series lies in the ultra-violet, the terms $M=3$ having been computed as in the case of copper:

	$M=2$	$M=3$
λ.....	3280.8 Observed	2061.3 Computed
ν.....	30471.7	48498.3
Mp_1.....	30620.7	12594.1
λ.....	3383.0	2070.0
ν.....	29551.3	48295.4
Mp_2.....	31541.1	12797.0

SUBORDINATE SERIES II

$2p_1$=30620.7 [Ritz]*			
M.....	1.5	2.5	3.5
λ.....	3280.80	8274.1	4668.70
ν.....	30471.7	12082.6	21413.3
Ms.....	61092.4	18538.1	9207.4
$2p_2$=31541.1			
λ.....	3383.00	7688.2	4476.29
ν.....	29551.3	13003.4	22333.8
Ms.....	61092.4	18537.7	9207.3

* *Annalen der Physik*, 12, 300, 1903.

SUBORDINATE SERIES I

$2p_1$=30620.7			
M.....	3	4	5
λ.....	5465.66	4212.1	3810.6
ν.....	18291.0	23734.5	26235.2
Md.....	12329.7	6886.2	4385.5
λ.....	5471.72		
ν.....	18270.8		
Md'.....	12349.9		
$2p_2$=31541.1			
λ.....	5209.25	4055.44	3681.8
ν.....	19191.3	24651.3	27152.9
Md'.....	12349.8	6889.8	4388.2

The values of $4d^i$ and $5d^i$ are, within the limits of observational error, practically equal to $4\Delta p$ and $5\Delta p$; so that it is possible that the lines 4212.1, 4055.44, 3810.6, and 3681.8 correspond to the combination $2p_i - M\Delta p$ instead of belonging to the subordinate series I as Kayser and Runge write them.

With the four following substances, caesium, rubidium, strontium, and barium, the fused chloride, moisture free, was used in the arc. The current was in general 20 amperes. The spectra of all the materials were twice examined to 30,000 Å.U., except rubidium. Here only those lines were measured which had been found by Moll or whose positions were foretold by the Ritz combination principle.

CAESIUM

Int.....	130	20	250	10	250	30
Order...	I	I	I	I	I	I
	8021.5	8017.7	8083.3	8080.7	8524.2	8522.6
	19.4	19.1	3.6	0.9	1.7	2.6
	21.0	19.4	2.4	0.9	4.5	2.6
		19.4			4.0	1.5
		19.0			4.4	2.9
Mean...	8020.6	8018.9±2.0	8083.1	8080.9±2.0	8523.8	8522.4±1.5
ν.....		12467.0		12371.5		11730.6

Int.....	230	20	270	40	350	40
Order...	I	I	I	I	I	I
	8761.5	8762.0	8947.0	8945.0	9173.3	9172.1
	1.0	3.0	4.7	4.5	3.5	4.2
	2.6	2.6	3.3	4.8	3.4	4.6
			5.3	5.1	2.5	3.7
					4.9	
	8761.7	8762.5	8945.1	8944.9	9173.5	9173.9
Mean...		8762.1±1.5		8945.0±1.5		9173.7±1.0
ν.....		11409.7		11176.6		10897.8

Int.....	170	10	200	5	200	5
Order...	I	I	I	III	I	III
	9210.5		10026.0			
	08.9		5.4		10124.1	
	08.7		5.6	10025.5	3.8	10124.0
	10.2	9209.3				
	10.0	10.3				
	9209.7	9209.8				
Mean.		9209.7±1.0	10025.7	10025.5±0.5	10124.0	10124.0±0.5
ν.....		10855.2		9971.78		9874.86

Int.....	80	12	100	20
Order...	I	I	I	II
	13591.7	13761.0	14698.1	14695.9
	0.5	1.4	7.0	6.2
	0.0	1.7	7.1	7.0
	1.3			
	0.1			
Mean...	13590.7±1.5	13761.4±1.5	14697.4	14696.4±1.5
ν.....	7356.06	7264.75		6802.51

Int.....	6	6
λ.....	29318.5	30103.1
	7.8	4.2
	7.5	4.0
	6.0	
Mean.....	29317.4±2.0	30103.8±3.0
ν.....	3410.04	3320.92

The spectrum of caesium shows relatively many strong lines, but most of these are quite broad, only two, 10025.7 and 10124.0, being sufficiently sharp to give definite maxima in the higher orders. To increase the sharpness of the lines, measurements were made with but small quantities of the salt in the arc, and the results show that certain lines, notably 8083.1 and 8523.8, give smaller readings, while others are apparently unchanged. As many of the caesium lines are broadened toward the red it is probable that the smaller values are the more correct; they give in general better agreements

when they enter into Ritz combinations.[1] An attempt to sharpen the lines by reduced pressure about the arc only resulted in so decreasing the intensity of the lines that no measurements could be made.

8522.4.....	$1.5s-2p_1$	Principal series
8945.0.....	$1.5s-2p_2$	Principal series
14696.4.....	$2p_1-2.5s$	Subordinate series II
13590.7.....	$2p_2-2.5s$	Subordinate series II
9173.7.....	$2p_1-4d$	Subordinate series I
9209.7.....	$2p_1-4d'$	Subordinate series I
8762.1.....	$2p_2-4d'$	Subordinate series I
30103.8.....	$2p_2-3d'$	Subordinate series I
10025.5.....	$3d'-4\Delta p$	Bergmann series
10124.0.....	$3d-4\Delta p$	Bergmann series
8018.9.....	$3d'-5\Delta p$	Bergmann series
8080.9.....	$3d-5\Delta p$	Bergmann series

29317.4.....	$2.5s-3p_1$	29292.8 Comp.	Ritz combination
13761.4.....	$3p_2-3d'$	13757.4 Comp.	Ritz combination

Previous determinations—

Moll: 0.803, 0.855, 0.895, 0.920, 1.01, 1.12, 1.37, 1.48, 3.00 in μ.

Lehmann: 8019.62, 8082.02, 8527.72, 8766.10, 8949.92, 9171.38, 9211.86 in $\mu\mu$.

Bergmann: 1002.8, 1012.7, 1359.7, 1377.1, 1476.6 in $\mu\mu$.

PRINCIPAL SERIES

$1.5s=31397.8$

M.....	2	3	4
λ.....	8522.4	4555.44	3876.73
ν.....	11730.6	21945.8	25787.7
Mp_1.....	19667.2	9452.0	5610.1
λ.....	8945.0	4593.34	3888.83
ν.....	11176.6	21764.6	25707.5
Mp_2.....	20221.2	9633.2	5690.3

SUBORDINATE SERIES II

$2p_1=19667.2$

M.....	1.5	2.5	3.5
λ.....	8522.4	14696.4	7944.7
ν.....	11730.6	6802.51	12583.5
Ms.....	31397.8	12864.7	7083.7

$2p_2=20221.2$

λ.....	8945.0	13590.7	7609.7
ν.....	11176.6	7356.06	13137.5
Ms.....	31397.8	12865.1	7083.7

[1] Paschen, *Annalen der Physik*, **33**, 731, 1910.

SUBORDINATE SERIES I

$2p_1 = 19667.2$			
M	3	4	5
λ	34892.5*	9173.7	6973.1
ν	2865.2	10897.8	14336.9
Md	16802.0	8769.4	5330.3
λ	36127.7*	9209.7	6983.8
ν	2767.3	10855.2	14315.0
Md'	16899.9	8812.0	5352.2
$2p_2 = 20221.2$			
λ	30103.8	8762.1	6723.7
ν	3320.9	11409.7	14868.8
Md'	16900.3	8811.5	5352.4

* Paschen.

BERGMANN SERIES $3d^i - M\Delta p$

$3d' = 16900.1$				
M	4	5	6	7
λ	10025.5	8018.9	7228.8	6826.9
ν	9971.8	12467.0	13829.7	14643.9
$M\Delta p$	6928.3	4433.1	3070.4	2256.2
$3d = 16802.0$				
λ	10124.0	8080.9	7280.5	6872.6
ν	9874.7	12371.5	13731.6	14546.5
$M\Delta p$	6927.3	4430.5	3070.4	2255.5

RUBIDIUM

Int.	160	5	5	100
λ	10080.1	12924.4	12987.2	13236.8
	3.5	5.5	8.3	6.8
	1.7	2.3	4.5	8.0
	2.4			6.6
				7.1 (30)*
Mean	10081.9±1.5	12924.1±3.0	12986.6±3.0	13237.0±1.0
ν	9916.11	7735.39	7698.17	7552.57
Int.	270	150	150	100
λ	13444.8	13668.4	14754.0	15289.6
	3.9	7.8	4.5	91.0
	2.9	6.9	3.5	90.3
	3.5	6.5(15)*	3.8	90.6(15)*
	3.4		4.4(10)*	
	4.8(30)*			
Mean	13443.9±1.5	13667.4±1.5	14754.0±1.0	15290.4±1.5
ν	7436.33	7314.70	6776.03	6538.34
Int.	35	12	8	8
λ	22533.0	22936.6	27319.9	27910.3
	3.1	7.6	18.8	9.3
	2.7	6.3	20.8	9.7
	3.3	6.4		
Mean	22533.0±0.8	22936.7±1.0	27319.8±2.0	27909.8±2.0
ν	4436.75	4358.67	3659.37	3582.01

* None of the rubidium lines shows decrease in value when intensity is lowered to amount indicated by the number in brackets.

Previous determinations—
Moll: 1.01, 1.35, 1.51, 2.28, 2.80 in μ.
Bergmann: 1006.9, 1322.3, 1344.2, 1366.6, 1483.0, 1541.0 in $\mu\mu$.

13667.4.....	$2p_1 - 2.5s$			Subordinate series II
13237.0.....	$2p_2 - 2.5s$			Subordinate series II
15290.4.....	$2p_1 - 3d$			Subordinate series I
14754.0.....	$2p_2 - 3d'$			Subordinate series I
13443.9.....	$3d - 4\Delta p$			Bergmann series
10081.9.....	$3d - 5\Delta p$			Bergmann series
22533.0.....	$3d - 3p_1$	22533.2	Computed	Ritz combination
22936.7.....	$3d - 3p_2$	22934.5	Computed	Ritz combination
27319.8.....	$3p_1 - 2.5s$	27313.3	Computed	Ritz combination
27909.8.....	$3p_2 - 2.5s$	27904.9	Computed	Ritz combination
12924.1.....	$4p_1 - 2.5s$	12920.8	Computed	Ritz combination
12986.6.....	$4p_2 - 2.5s$	12979.5	Computed	Ritz combination

PRINCIPAL SERIES

Limit $1.5s = 33694.0$

M.....	2	3	4
λ.....	7800.2	4201.98	3587.23
ν.....	12816.7	23791.7	27868.9
Mp_1.....	20877.3	9902.3	5825.1
λ.....	7947.6	4215.72	3591.74
ν.....	12579.0	23714.1	27833.9
Mp_2.....	21115.0	9979.9	5860.1

SUBORDINATE SERIES II

$2p_1 = 20877.3$

M.....	1.5	2.5	3.5
λ.....	7800.2	13667.4	7408.5
ν.....	12816.7	7314.70	13494.3
Ms.....	33694.0	13562.6	7383.0

$2p_2 = 21115.0$

λ.....	7947.6	13237.0	7280.3
ν.....	12579.0	7552.5	13731.9
Ms.....	33694.0	13562.5	7383.1

SUBORDINATE SERIES I

M.....	3	4	5
λ.....	15290.4	7757.9	6298.7
ν.....	6538.34	12886.6	15872.0
Md.....	14338.96	7990.7	5005.3
		7759.5	
		12883.9	
Md'.....		7993.4	
λ.....	14754.0	7619.2	6206.7
ν.....	6776.03	13121.1	16107.2
Md'.....	14339.02	7993.9	5007.8

BERGMANN SERIES

$3d = 14339.0$

	4	5	6
λ.....	13443.9	10081.9	8872.
ν.....	7436.33	9916.11	11268.4
$M\Delta p$.....	6902.7	4422.9	3070.6

STRONTIUM

Int....	100	200		200	
Order..	I	I	II	I	II
λ.....	10038.6	10329.9	10328.6	10916.4	10915.2
	8.6	7.9	8.0	7.5	4.5
	7.7	8.3		5.2	5.2
				6.1	
Mean..	10038.3±1.0	10328.7	10328.3±0.8	10916.3	10915.0±0.8
ν.....	9959.16		9679.32		9159.19

Int.....	50	10	6	6
λ.....	11243.4	20262.5	26023.8	26914.5
	4.2	3.0	4.6	5.0
	2.3	3.1	5.0	5.7
	1.1			6.3
Mean.....	11242.7±2.0	20262.9±1.0	26024.5±1.0	26915.4±1.5
ν.....	8892.30	4933.81	3841.50	3714.34

Int.....	6	6	5
λ.....	27356.2	29226.4	30109.5
	6.4	5.1	11.2
	5.9	6.2	11.4
Mean.....	27356.2±1.5	29225.9±1.5	30110.7±3.0
ν.....	3654.50	3420.72	3320.2

Previous determinations—Lewis: 10326.8, 10915.7.

THE FIRST TERM OF THE SUBORDINATE SERIES I OF TRIPLETS

	$2p_1 = 31026.1$ Group I	Δν	$2p_2 = 31420.5$ Group II	Δν	$2p_3 = 31607.7$ Line III	Mean
	[30667]*		27356.2		26024.5	
	3260.0	394.5	3654.5	187.0	3841.5	
$3d''$.....	27766.1		27766.0		27766.2	27766.1
	30110.7		26915.4			
	3320.2	394.1	3714.3			
$3d'$.....	27705.9		27706.2			27706.0
	29225.9					
	3420.7					
$3d$.....	27605.4					27605.4

* Estimated.

The differences between the terms $3d^i$, 100.6 and 60.1, and the close agreement between the value of $3d$ and the limit which

Fowler[1] gives for the less refrangible components of the narrow strontium triplets discovered by him, indicate that this series, as well as the corresponding Saunders series of calcium,[2] is of the Bergmann type and that it may be represented by the expression $3d^i - M\Delta p$.

The following arrangements of lines, corresponding to similar arrangements in calcium,[3] seem possible.

20262.9 $1.5s - 3p_1$ As $1.5s = 16887.1$ $3p_1 = 11953.3$ Principal series of triplets

With this value of $3p_1$ the term 12012.1 which appears in the following combinations may be considered to be $3p_2$.

		$3d$	$3d'$	$3d''$
$3p_1$.....	Observed	6386.74	6345.9*	
	Computed	6387.2	6346.4	
$3p_2$.....			6370.2	6345.9*
			6370.2	6345.9
$3p_3$.....	[12057.6?]			[6364.3]?

* Used twice, as also is done in calcium.

5257.12	$2p_1 - 3p_2$	5257.8 Computed
10038.3	$2p_1 - 3d'$	Subordinate series I of doublets
10328.3	$2p_1 - 3d$	
10915.0	$2p_2 - 3d'$	

BARIUM

Int.....	100	100	20	70
λ.....	9530.1	9613.6	9714.1	9833.4
	23.9	10.5	13.3	0.8
	27.5	7.8	12.7	0.8
	27.5	10.9		
Mean.....	9527.3±3.5	9610.7±3.0	9713.4±1.5	9831.7±1.5
ν.....	10493.3	10402.2	10292.3	10168.5
Int.....	25	60	5	60
λ.....	10002.9	10036.0*		
	1.0	4.7		
	2.5	2.5		10233.3
	2.0	7.2	10189.4	4.3
		7.5	8.9	4.0
Mean.....	10002.1±1.0	10035.6±3.0	10189.1±2.0†	10233.8±1.0
ν.....	9995.3	9961.8	9811.8	9768.95

* 10038.3, 29225.9 } not strontium, as the strongest strontium lines are lacking.

† In the preliminary paper a misprint made this line 10199.1.

[1] *Astrophysical Journal*, **21**, 82, 1905.

[2] *Annalen der Physik*, **29**, 657, 1909. [3] *Op. cit.*, p. 658.

Int.....	5	60	70	10
λ.....	10272.2	10475.3		
	3.6	10474.7		23254.8
		3.2	10652.4†	4.7
Mean.....	10272.9±2.0	10474.4†		23254.8±2.0
ν.....	9731.7	9544.5	9385.0	4299.0

Int.....	10
	29224.0*
	2.7
	3.6
Mean.....	29223.4±2.0
ν.....	3421.0

* 10038.3, 29225.9 } not strontium, as the strongest strontium lines are lacking.

† But once found; possibly *Pb*.

8210.73*	$2p_1-3d'$	Subordinate	As $2p_2=51616.4$	$3d'=62101.7$
8654.33*	$2p_1-3d$	series I	$2p_1=49925.8$	$3d=61477.6$
9527.3	$2p_2-3d'$	of doublets		$3d'=62109.7$
10233.8	$1.5s-3d'$	10230.8 Computed		$1.5s=71877.5$
9610.7	$1.5s-3d$	9612.8 Computed		
29223.4	$2p_1-3d'$	Subord. series I	As $2p_1=28472.0$	$3d'=$ 25051.0, 25051.4
23254.8	$2p_2-3d'$	of triplets	$2p_2=29350.4$	

* Hermann, Dissertation, Tübingen, 1907.

The above arrangements are somewhat doubtful.

TIN

Intensity	Wave-Length	Error	Frequency
12	8554.7	1.5	11686.3
8	9023.2	1.5	11079.8
7	9414.9	2.0	10618.6
6	9619.4	2.0	10392.8
6	9746.0	1.0	10257.9
6	9808.7	2.0	10192.3
10	9852.5	1.0	10147.0
10	10458.6	1.5	9558.95
12	10808.8	1.0	9249.24
40	10896.0	1.5	9175.24
70	11194.0	1.0	8930.96
120	11279.2	1.0	8863.52
10	11339.4	1.0	8816.47
60	11457.3	1.0	8725.70
65	11618.0	1.0	8605.04
20	11672.6	1.0	8564.80
90	11741.9		
8*	11740.4*	0.5	8515.28
40	11827.2	1.0	8452.80
40	11853.3	2.0	8434.19
170	11935.3		
10*	11934.0*	1.0	8377.18
50	12982.9	1.0	7700.36
25	13022.0	1.0	7677.25

*Second order.

LEAD

Intensity	Wave-Length	Error	Frequency
100	10292.9		
10*	10291.3*	0.5	9714.30
150	10501.3		
15*	10500.0*	0.5	9521.22
60	10650.8	2.0	9386.40
12	10888.6	2.0	9181.46
30	10971.5	1.0	9112.14
40	12563.8	1.0	7957.21
40	13101.9	1.0	7630.45
30	14744.4	1.0	6780.46
30	15315.6	1.0	6527.54

* Second order.

ARSENIC†

Intensity	Wave-Length	Error	Frequency
10	8823.3	1.0	11330.6
15	8871.2	1.0	11269.4
15	8936.9	1.5	11186.5
100	9599.3	1.0	11414.6
140	9627.7	1.0	10383.9
80	9834.1	1.0	10166.0
150	9923.2	1.0	10074.7
100	10024.4	2.0	9972.98
60	10453.8	1.5	9563.32
25	10614.6	1.5	9418.48

Arsenic was examined to but 16,000 Å.U.

ANTIMONY

Intensity	Wave-Length	Error	Frequency
20	9519.9	2.0	10501.5
15	9950.5	2.0	10047.2
35	10079.9	1.5	9918.07
40	10262.9	1.5	9741.25
50	10587.2	1.0	9442.87
130	10678.6		
10*	10678.0*	0.5	9362.60
50	10742.9	1.0	9305.96
50	10840.6	1.0	9222.10
30	10880.3	2.0	9188.46
20	11013.4	1.5	9077.37
15	11082.7	1.5	9020.62
15	11109.7	2.0	8998.72
10	11190.3	2.0	8933.90
45	11268.5	1.0	8871.94
40	11864.3	1.0	8426.36
15	12118.9	1.5	8249.32

* Second order.

BISMUTH

Intensity	Wave-Length	Error	Frequency
7	7841.1	1.5	12749.9
10	8628.5	2.0	11586.4
10	8761.8	1.5	11410.2
10	8910.0	1.5	11220.3
15	9059.5	2.0	11035.2
40	9344.1		
5*	9343.6*	0.5	10699.7
300	9657.9		
20*	9657.7*	0.5	10351.7
20	9828.8	1.0	10171.5
20	10106.1	1.0	9892.38
15	10301.7	2.0	9704.50
8	10540.2	2.0	9484.98
15	11073.2	1.0	9028.38
5	11555.5	2.0	8651.58
160	11711.9		
10*	11711.1*	1.0	8536.66
13	11994.5	2.0	8334.94
40	12166.5	1.0	8217.05
30	12690.5	1.0	7877.82
25	14331.5	1.5	6975.78
7	22554.2	1.0	4432.57

*Second order.

In the preceding tables the average values only of the measured wave-lengths are given. Each line was measured at least three times, the individual determinations being on different days. With these elements but a single examination of the spectrum between 7000 and 30,000 Å.U. was made in each case. The arcs burned so quietly that there was not much possibility of overlooking lines whose intensity was 10 mm.

This investigation was conducted in the Physical Laboratory of the University of Tübingen, and the writer wishes to express his appreciation of the many courtesies extended to him by its director, Professor F. Paschen, and also his great indebtedness for the many valuable suggestions so kindly offered.

PHYSICAL LABORATORY
UNIVERSITY OF MICHIGAN
January 1911

THE EFFECT OF PRESSURE ON THE ARC SPECTRUM OF VANADIUM

By R. ROSSI

This research was carried out in the same manner as a previous one on the effect of pressure on the arc spectrum of titanium;[1] the region studied being again from λ 4000 to λ 4600.

The same apparatus was used, the arc being struck between a carbon pole and a graphite tube filled with vanadium carbide. The vanadium arc under pressure does not burn as well as the titanium, so that at high pressures very long exposures of the photographic plates were needed, with the result that the plates were often fogged owing to the continuous spectrum due to the carbon poles. Photographs at 100 atmospheres were especially hard to obtain, the exposure sometimes amounting to one hour. This accounts for the lack of readings at that pressure, as will be noticed in the table given below. Two sets of photographs were chosen at 15, 30, 50, and 100 atmospheres, and these were employed in all subsequent measurements. (See Plates I and II.)

All lines were found to be broadened and displaced toward the less refrangible end of the spectrum by pressure. Several lines were found to be reversed; they are marked *R* and *r* in the last column of Table I according to their large or small tendency to reverse under pressure. The wave-lengths are taken from Hasselberg's tables.[2] The displacements were measured by means of a Kayser measuring machine, 12 readings being taken for each line on each plate.

It will be noticed that the displacements do not vary much from line to line, with the result that no grouping of lines of equal shift was possible.

The mean displacement of all vanadium lines studied at each pressure is given in Table II, which also confirms once more the approximate linear relation between pressure and displacement. The mean displacement per atmosphere of all vanadium lines is found to be 0.00266 Ångström unit.

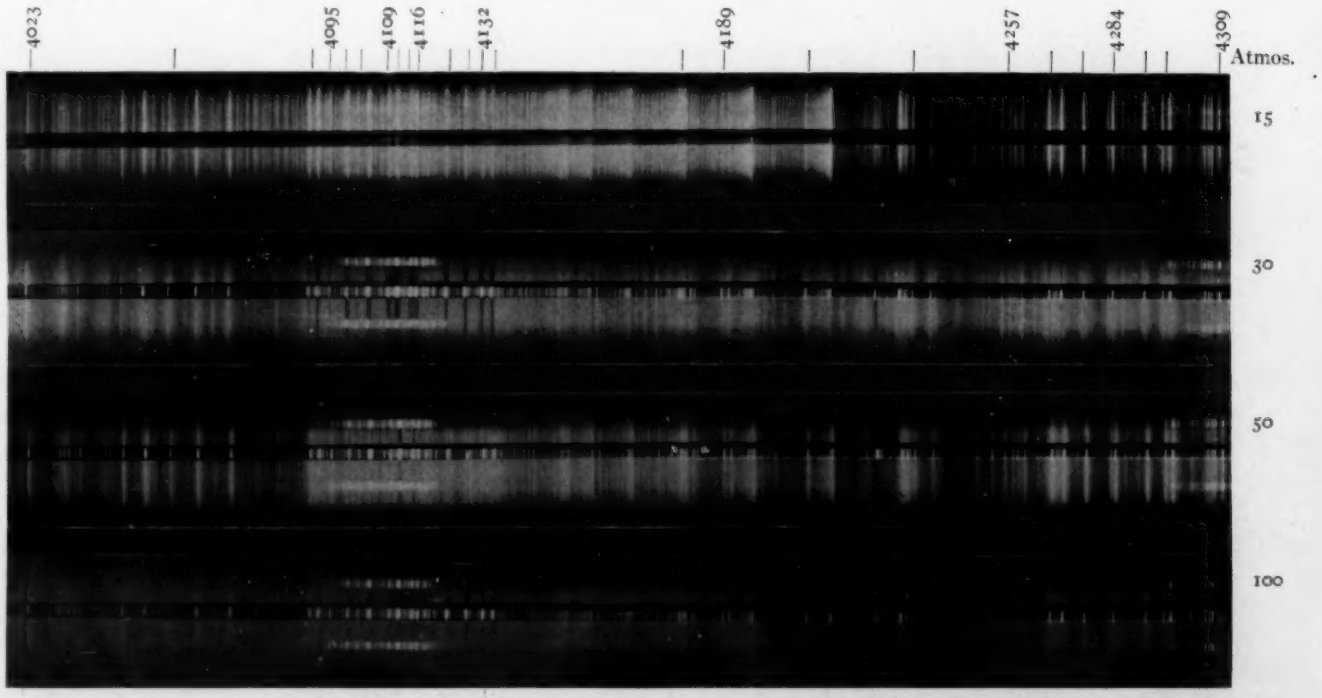
[1] *Proc. Roy. Soc.*, A, 83, 414, 1910. [2] *Astrophysical Journal*, 11, 67, 1900.

TABLE I

Atmospheres....	15	30	50	100	
Wave-Length	Displacements in thousandths of an Å.U.				Tendency to Reverse
4023.50.....	47	68	...	(199)	...
57.21.....	58	112	175	309	...
90.70.....	71	93	174	...	R
95.64.....	61	91	149	...	r
99.93.....	49	80	134	...	R
4102.32.....	47	89	...	...	r
09.94.....	52	83	131	...	R
11.92.....	43	92	108	...	R
15.32.....	43	91	128	...	R
16.64.....	42	89	(121)	...	R
23.65.....	50	92	147	259	R
28.25.....	46	94	150	270	R
32.13.....	49	93	142	243	R
34.61.....	44	92	141	274	R
79.53.....	..	(82)	...	...	r
89.99.....	..	99	147	...	r
4209.98.....	46	95	144	...	r
35.90.....	43	80	122	...	..
57.53.....	41	104	149	290	..
68.78.....	47	89	(133)	...	r
77.12.....	47	89	156	246	r
84.19.....	53	90	164	...	r
91.97.....	46	92	164	261	r
96.28.....	46	93	138	...	r
4309.95.....	38	85	129	...	..
30.18.....	42	78	(120)	(259)	r
32.98.....	41	72	113	(227)	r
41.15.....	52	77	134	...	r
53.02.....	40	75	130	...	r
79.38.....	46	92	122	266	R
84.87.....	46	93	124	233	R
90.13.....	43	86	119	234	R
95.40.....	47	78	(131)	268	R
4400.74.....	47	82	133	208	R
12.30.....	43	79	139	...	r
16.63.....	43	85	148	...	r
20.08.....	40	87	128	...	r
21.73.....	46	85	(128)	...	r
26.17.....	44	84	...	...	r
28.68.....	46	86	146	...	r
29.95.....	47	87	146	...	r
36.31.....	49	80	139	...	r
38.02.....	43	80	142	...	r
41.88.....	50	81	121	...	r
44.40.....	49	83	139	...	r
52.19.....	50	79	132	...	r
62.56.....	51	82	138	...	r
68.19.....	42	91	116	...	r
69.88.....	50	96	144	...	r
80.20.....	39	103	156	190	..
4502.12.....	38	91	106	160	..

Figures in parentheses denote doubtful readings.

PLATE I



EFFECT OF PRESSURE ON THE ARC SPECTRUM OF VANADIUM

Central strips at atmospheric pressure; outer strips at pressures indicated on margin
Wave-lengths are given for every fourth line of Table I

TABLE I (*Continued*)

Atmospheres....	15	30	50	100	
Wave-Lengths	Displacements in thousandths of an Å.U.				Tendency to Reverse
4514.36.....	47	109	179	...	..
24.38.....	41	87	142	251	r
45.57.....	48	81	137	234	r
49.81.....	42	86	145	274	r
60.90.....	43	83	134	230	r
71.96.....	44	80	130	243	r
77.36.....	44	72	125	...	r
80.57.....	42	68	123	...	r
83.96.....	43	81	115	...	r
91.39.....	46	86	128	246	..
94.27.....	41	68	114	...	r

TABLE II

Pressure in Atmospheres (Excess above One Atmosphere)	15	30	50	100
Mean displacement in Å.U.....	0.042	0.082	0.132	0.245
Mean displacement per atmosphere in Å.U.	0.0028	0.0027	0.0026	0.0024

The relative intensities of the vanadium lines are very little affected by pressure. A few lines show very slight changes in intensity, but these changes are not always the same on all photographs. Only the two lines λ 4095.5 and λ 4102.3 show an appreciable decrease in intensity with increase of pressure; on some plates at 100 atmospheres they are quite obliterated.

It has often been claimed on theoretical grounds that there should exist a connection between the pressure-displacement and the Zeeman effect. A. S. King[1] recently collected a number of data for lines on which both phenomena have been studied and came to the conclusion that there seems to be a correspondence between the magnitudes of the two effects for the majority of the lines considered.

The magnetic separation of the vanadium lines has been studied in a very exhaustive paper by Purvis,[2] and his results are compared with the pressure-displacements in Table III. They are

[1] *Astrophysical Journal*, **31**, 433, 1910.

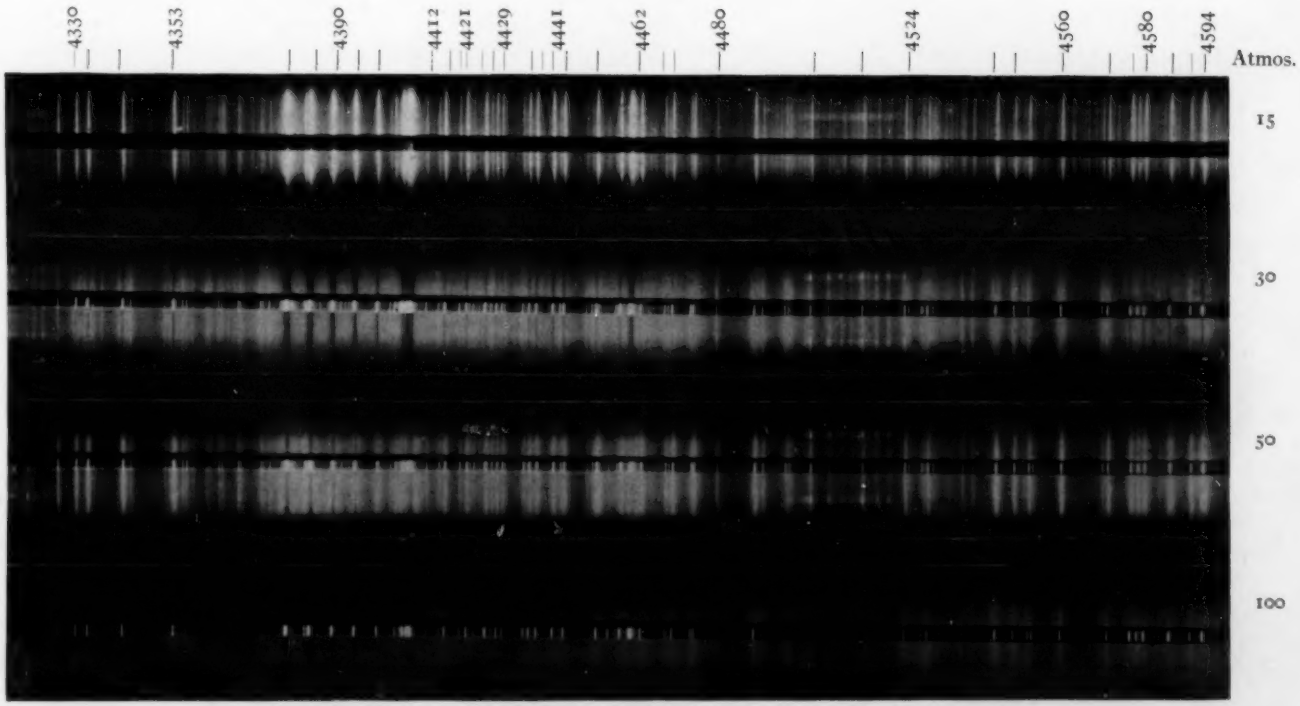
[2] *Cambridge Phil. Soc., Trans.*, **20**, 193.

TABLE III

Wave-Length	Mean Pressure-Displacement per Atmosphere in 10^{-5} Å.U.	Magnetic Separation in 10^{-3} Å.U.	R
		TRIPLETS	
4023.50	247	498	2.02
90.70	377	524	1.39
95.64	337	517	1.53
4102.32	305	378	1.24
15.32	283	762	2.69
28.25	297	710	2.39
32.13	290	728	2.51
34.61	287	728	2.53
4268.78	293	634	2.16
77.12	292	564	1.93
84.19	327	270	.82
91.97	302	572	1.89
96.28	300	572	1.90
4332.98	257	636	2.47
41.15	293	634	2.16
53.02	260	698	2.68
79.38	282	642	2.27
84.87	275	634	2.30
90.13	262	530	2.02
4426.17	285	1057	3.70
28.68	297	1010	3.70
52.19	283	600	2.12
62.56	297	578	1.94
4469.88	313	570	1.82
4545.57	275	500	1.88
60.90	267	510	1.91
71.96	265	502	1.85
77.36	260	380	1.46
80.57	253	566	2.23
94.27	263	650	2.47
		QUADRUPLETS	
4209.98	307	590*	1.92
4395.40	275	410*	1.49
4416.63	290	622	2.14
		1651	5.69
4421.73	283	260	.92
		1290	4.55
4436.31	293	236	.80
		1074	3.67
4438.02	280	156	.56
		957	3.42
4441.88	280	248	.88
		951	3.39
4444.40	297	448	1.51
		1231	4.14

* Inner doublet of quadruplet.

PLATE II



EFFECT OF PRESSURE ON THE ARC SPECTRUM OF VANADIUM

Central strips at atmospheric pressure; outer strips at pressures indicated on margin
Wave-lengths are given for every fourth line of Table I

TABLE III (*Continued*)

Wave-Length	Mean Pressure-Displacement per Atmosphere in 10^{-3} Å.U.	Magnetic Separation in 10^{-3} Å.U.	*R*
	QUINTUPLETS		
4116.64.....	273	801 1690	2.93 6.19
4400.74.....	265	610 1114	2.30 4.20
	SEXTUPLETS		
4109.94.....	297	348 422 1242	1.17 1.45 4.18
4123.65.....	297	350 428 1246	1.17 1.44 4.19

arranged according to the type of magnetic separation (triple, quadruple, etc.). The separations are for a field of 39,980 C.G.S. units, perpendicular to the lines of force. The column headed *R* gives the ratio of the magnetic separation to the pressure-displacement. No grouping of lines giving the same value of *R* seems possible.

It is known that the magnetic separation increases with the square of the wave-length, but an exact relation between the pressure-displacement and wave-length has not yet been found. The displacement seems to be roughly proportional to the square or a higher power of the wave-length,[1] so that the values given in Table III may not be comparable. Comparisons were therefore also made between the magnetic separation and the pressure-displacements divided by the wave-length, its square, and its cube; thus assuming the displacements to vary respectively from the cube to the fifth power of the wave-length; but even then no grouping of lines seemed possible.

In conclusion I wish to express my thanks to Professor Rutherford for placing the necessary apparatus at my disposal, and to Professor Schuster for the interest he has taken in this work.

MANCHESTER UNIVERSITY
December 1910

[1] Duffield, *Phil. Trans. Roy. Soc.*, A, **209**, 205, 1908.

PHOTOGRAPHIC DETERMINATIONS OF STELLAR PARALLAX MADE WITH THE YERKES REFRACTOR. VII

By FRANK SCHLESINGER

SUMMARY AND DISCUSSION

The results are summarized in Table IV. The magnitudes and the assignment of spectra are for the most part copied from the recent compilation of parallaxes by Kapteyn and Weersma in *Groningen Publications*, No. 24. The third column from the last informs us in what directions the displacements were measured.

The list contains three double stars of which both components were measured. The difference for each pair of parallaxes, and the square root of the sum of the squares of their probable errors, are as follows:

	Difference	$\sqrt{\epsilon_1^2+\epsilon_2^2}$
Groombridge 34	0".013	±0".022
Fedorenko 1457–58 (R.A.)	.023	.038
" " (decl.)	.033	.048
P.M. 2164 (R.A.)	.001	.007
" " (decl.)	.028	.022

A more severe test as to the presence of systematic error is afforded by comparing the results from the declination displacements with those from the right ascensions:

	Difference R.A. *minus* Decl.	Probable Error
Fedorenko 1457 (preceding star)	+0".027	±0".044
" *1458* (following ")	+ .037	.043
Lalande 23917	+ .060	.048
Fedorenko 2544	+ .028	.031
P.M. 2164 (preceding star)	− .005	.013
" " (following ")	− .034	.020
Groombridge 3689	− .062	.023
Krüger 60	+ .019	.013
Lalande 46650	+ .066	.036

Five of these differences exceed the probable error and four are less than it.

The complete observing list for this work contained a number of stars of the helium type. The intention was to ascertain by observation whether these stars are at the great distance that their proper

motions would imply. The results for four of these stars appear in the present table: *c Persei*, π^4 *Orionis*, ψ *Orionis*, and *S Monocerotis*. Three of these parallaxes come out negative and the fourth is only slightly positive; so far then as they go, they confirm the inference drawn from their proper motions. If we take the mean of these four parallaxes, weighting them in accordance with their probable errors, we obtain $-0''.006 \pm 0''.005$, indicating that these fourth magnitude stars are nearly or quite as distant as the ninth magnitude stars in the same regions of the sky.

With the exception of these helium stars none of the deduced parallaxes come out negative. This is also true of the separate results (for the two co-ordinates, and for the two components of double stars) with the exception of the value from the declinations of *Lalande 23917;* and in this case the negative value is much less than its probable error.

In connection with the detailed results for each star, I have given the determinations by other observers, in order that the reader may see how the present values agree with theirs. A careful study of the recent and extensive series of parallax determinations, from the point of view of systematic error, is well worth while; but it would be out of place here.

The average number of plates of each region is thirteen. This is also about the number than can be secured during a clear night of average length and under average atmospheric conditions. The average probable error of one of our parallaxes is $\pm 0''.013$. We may therefore state this conclusion, which will be important in planning similar work in the future: *With a telescope of this size and character, the number of stellar parallaxes that can be determined per annum with an average probable error of* $\pm 0''.013$ *will (in the long run) be about equal to the number of clear nights available for this work.*

This statement does not neglect the fact that in most situations there is more cloudy weather in winter than in summer. This will be compensated for by the fact that a winter night is *for this purpose* at least three times as valuable as a summer night, not only on account of its greater length, but also because it is possible to secure plates for which the parallax factors are on the average considerably greater, always assuming that the exposures are to be made when the regions are near the meridian.

TABLE IV

Summary of Results

Star	R.A. 1900	Decl. 1900	*B.D.* Number	Magnitude and Spectrum	Proper Motion	Relative Parallax	Probable Error	Co-ord.	No. of Plates	Probable Error of One Plate
Groombridge **34**	$0^h\ 13^m$	$+43°\ 27'$	$+43°44$	8.2, Ma	2".85	+".256	±".019	long.	12	±0".040
Groombridge **34** (Companion)				10, —		+.269	.011	long.	10	.019
					Mean	+.**266**	.01			
μ Cassiopeiae	1 2	+54 26	+54°223	5.3, G5	3.75	+.**105**	.010	long.	9	.019
Lalande **5761**	3 3	+25 58	+25°495	8.0, F2	0.90	+.**010**	.020	long.	10	.046
Lalande **7443**	3 56	+35 3	+34°796	8.6, G2	2.19	+.**039**	.013	long.	11	.025
c Persei	4 1	+47 27	+47°939	4.0, B3	0.05	+.**008**	.009	long.	8	.016
π⁴ Orionis	4 46	+ 5 26	+ 5°745	3.8, B3	0.01	−.**012**	.007	long.	11	.014
ψ Orionis	5 22	+ 3 1	+ 2°962	4.7, B2	0.01	−.**019**	.015	long.	14	.029
Weisse I, 5^h **592**	5 26	− 3 42	− 3°1123	8.9, Ma	2.23	+.**189**	.010	long.	18	.027
S Monocerotis	6 35	+ 9 59	+10°1220	4.7, Oe5	0.01	−.**007**	.012	long.	8	.022
Lalande **13427**	6 54	+48 32	+48°1469	8.2, —	0.71	+.**049**	.011	long.	10	.022
Lalande **15290**	7 47	+30 55	+31°1684	8.2, Go	1.97	+.**072**	.019	long.	14	.042
Fedorenko **1457**	9 8	+53 7	+53°1320	7.9, Ma	1.69	+.172	.025	R.A.	12	.044
Fedorenko **1457**						+.145	.036	decl.	12	.027
Fedorenko **1458**			+53°1321	7.9, Ma		+.149	.028	R.A.	12	.050
Fedorenko **1458**						+.112	.032	decl.	12	.025
					Mean	+.**148**	.015			
Lalande **23917**	12 45	+ 1 45	+ 2°2585	8.3, —	0.68	+.035	.020	R.A.	13	.028
						−.025	.044	decl.	13	.029
					Mean	+.**025**	.018			

Berlin A **4999**	13^h	40^m	$+18°$	24′	$+18°2776$	9.6, G5	1″.92	+″.077	±″.014	long.	11	±0″.020
Lalande **25372**	13	41	+15	26	$+15°2620$	8.7, K5	2.33	+.152	.007	long.	11	.012
Fedorenko **2544** ...	14	52	+54	4	$+54°1716$	7.9, G	1.08	+.056	.019	R.A.	12	.027
								+.028	.025	decl.	12	.022
							Mean	+.046	.015			
Weisse I, $17^h.322$ ..	17	21	+ 2	14	$+2°3312$	7.8, Ma	1.36	+.14	.020	long.	16	.032
P.M. **2164** (prec.).	18	42	+59	29	$+59°1915$	8.8, K	2.28	+.281	.004	R.A.	23	.014
P.M. **2164** (prec.).								+.286	.012	decl.	22	.013
P.M. **2164** (fol.) ..						9.3, —		+.280	.006	R.A.	23	.019
P.M. **2164** (fol.) ..								+.314	.019	decl.	22	.020
							Mean	+.282	.003			
Lamont **18180**	18	53	+ 5	48	$+5°3993$	9.4, Ma	1.24	+.06	.012	long.	21	.027
Lamont **18816**	19	2	+ 7	29	$+7°3967$	9.3, —	0.80	+.036	.007	long.	11	.010
31 *b Aquilae*	19	20	+11	44	$+11°3833$	5.2, G5	0.96	+.101	.022	long.	10	.021
Lalande **39866**	20	35	+ 4	37	$+4°4510$	8.4, K	0.86	+.067	.022	long.	14	.033
Groombridge **3689** ..	22	3	+52	39	$+52°3112$	8.1, —	0.61	+.018	.014	R.A.	16	.031
								+.080	.018	decl.	16	.021
							Mean	+.041	.020			
Krüger **60**	22	24	+57	12	$+56°2783$	9.2, K5	0.92	+.257	.007	R.A.	19	.018
								+.238	.011	decl.	19	.014
							Mean	+.252	.006			
Lalande **46650**	23	44	+ 1	52	$+1°4774$	8.9, Ma	1.40	+.161	.014	R.A.	13	.021
								+.095	.033	decl.	12	.022
							Mean	+.151	.013			

If the observer should decide to determine his parallaxes with smaller accidental errors than the above, a greater number of plates would of course be required, and the total number of determinations would be cut down. But in the writer's opinion, it is not especially desirable to strive for any considerable reduction in the accidental errors at the present time. It may possibly be that modern methods are capable of yielding parallaxes that are free from *systematic* errors of the order of 0".01, but this remains to be proven.

TABLE V

TABULATION OF FINAL RESIDUALS

No. of Measures	No. of Exposures	Quality of Images	No. of Residuals*	Sum of Residuals
1	1	Good	2	±0.033
1	1	Fair	5	.074
1	1	Poor	6	.149
1	2	Good	5	.032
1	2	Fair	12	.184
1	2	Poor	7	.096
1	3	Good	90	.924
1	3	Fair	141	1.717
1	3	Poor	58	0.806
2	1	Good	0	.....
2	1	Fair	7	.063
2	1	Poor	0	.....
2	2	Good	10	.151
2	2	Fair	13	.140
2	2	Poor	3	.014
2	3	Good	82	.717
2	3	Fair	35	.402
2	3	Poor	21	.448

* In those cases in which displacements in two directions were measured, both residuals have been tabulated; and likewise for measurements of both components of a double star.

In Table V the residuals for all the plates have been grouped according to the number of exposures, the quality of the images, and whether the plate has been measured by one or both of the observers. The sums in the last column are of course taken without regard to sign. Most of the plates have three exposures, 11 per cent having two, and only 5 per cent having one exposure. This table is therefore not suited to answer the question as to what relative weights should be assigned to plates containing less

than three exposures, and for the same reason this question (since it applies to few plates) is not of great importance. Better information on this point can be obtained from a study of the separate residuals for each *exposure*. Such a study shows that a plate that contains one exposure is entitled to about half the weight of a plate that contains three; and that two exposures are but slightly inferior to three. But these ratios differ greatly for different regions: where the image of the parallax star is much larger than the others, one exposure is nearly as good as the full number. On the other hand, in those cases for which the rotating disk was used to reduce the light of the parallax star, or for which the latter was, to begin with, about equal to the comparison stars in brightness, then the weights are more nearly proportionate to the number of exposures.

Let us next inquire what improvement is brought about by measuring the plates in duplicate. The average of the 289 residuals referring to plates that contain three images and that were measured once is ±0.0119. The average of the 138 residuals referring to plates that contain three images and that were measured twice is ±0.0114. These figures indicate that the second measurement has increased the weight by only 9 per cent. Even this small increase has probably been exaggerated, as the quality of the plates that were measured twice averages better than those that were measured once. A somewhat greater improvement is indicated by the small number of residuals that refer to plates containing less than the full number of exposures. For practical purposes we may then conclude that *the measurement of the plates in duplicate adds only 10 per cent to their weights.*

It was principally for this reason that such duplicate measurements were discontinued after March, 1905. It is true that the two measurements serve to check each other and call immediate attention to discrepancies; but the same advantage is retained by the separate reduction of the three exposures that appear on each plate.

Finally, and most important of all, Table V can tell us how to weight plates of different quality. Taking the averages of the plates that contain three exposures (whether they were measured twice or not) we obtain

	Average Residual	Relative Weight
For the 172 "good" plates.....	±0.0095	1.00
" " 176 "fair" "	.0121	0.62
" " 79 "poor" "	.0159	0.36

Collecting these various results we have Table VI. These relative weights are not very different from those actually employed (Table III, p. 170, March); the latter were, in fact, derived in much the same way, but from preliminary and less numerous residuals. The chief difference between the two tables may be stated thus: the former (Table III) slightly underrates good plates.

TABLE VI

RELATIVE WEIGHTS

	Two Measurements			One Measurement		
	Good	Fair	Poor	Good	Fair	Poor
One exposure	0.50	0.31	0.18	0.45	0.28	0.16
Two exposures.....	0.80	0.50	0.29	0.72	0.45	0.26
Three exposures.....	1.00	0.62	0.36	0.90	0.56	0.32

Of the plates here discussed, twenty-one were secured with the telescope east of the pier, and (as a natural consequence) at hour-angles that differ considerably from the others for the same regions. The residuals for these plates are collected in Table VII. The last column gives the relative hour-angle, obtained by subtracting the weighted mean hour-angle for the other plates of that region from the hour-angle for the plate in question. The first three residuals in this table result from least-squares solutions that include the plates themselves. As there is only one of these plates for each region, new solutions without these plates are hardly worth while. For the five other regions, solutions were made from which these plates were excluded, and the resulting residuals are tabulated. The parallax factors in the fourth column refer either to right ascension or declination.

In some cases, notably *Weisse* 17^h322, these residuals show a decided systematic tendency; while in others, notably *P.M. 2164*, they seem to be accidental in character. We may at least conclude that reversing this telescope is not entirely unattended with

danger, so far as the relative positions of the parallax stars are concerned; in the writer's opinion, the observations should be strictly confined to one or the other position of the telescope.

TABLE VII

RESIDUALS FOR PLATES SECURED WITH THE TELESCOPE EAST OF PIER

STAR	PLATE	WEIGHT	PARALLAX FACTOR	RESIDUALS			RELATIVE HOUR-ANGLE
				Long.	R.A.	Decl.	
Lal. 5761	203	0.8	−0.97	+0″.07	.....	.....	2^{h}6 West
Lal. 7443	218	0.8	− .95	+ .05	.....	.....	1.9 West
W. 5^{h}592	131	0.2	+ .82	− .02	.....	.....	1.4 West
W. 17^{h}322	68	0.7	− .85	+ .20	.....	.....	2.0 West
	86	0.4	−1.01	+ .12	.....	.....	2.5 "
	93	0.5	−1.00	+ .06	.....	.....	2.4 "
P.M. 2164	84	1.0	− .74	.....	+0″.01	−0″.03	2.4 West
(preceding)	87	1.0	− .93	.....	− .02	− .01	2.3 "
	90	1.0	− .97	.....	+ .02	+ .02	2.5 "
	94	0.8	− .98	.....	+ .01	.00	2.1 "
	106	0.8	−1.00	.....	− .01	.00	1.3 "
	150	0.4	− .87	.....	− .03	+ .02	2.8 "
P.M. 2164 (following)	84	1.0	− .74	.....	− .01	+ .01	2.4 West
	87	1.0	− .93	.....	+ .01	.00	2.3 "
	90	1.0	− .97	.....	+ .01	− .01	2.5 "
	94	0.8	− .98	.....	− .02	− .01	2.1 "
	106	0.8	−1.00	.....	− .03	− .03	1.3 "
	150	0.4	− .87	.....	− .17	− .11	2.8 "
Lam. 18180	57	0.2	− .42	+ .11	.....	.....	0.9 West
	76	0.8	− .62	+ .04	.....	.....	1.8 "
	107	0.9	− .98	+ .02	.....	.....	0.4 "
	111	0.9	−1.00	+ .09	.....	.....	2.7 "
	136	0.8	− .95	+ .09	.....	.....	1.8 "
Gr. 3689	170A	0.7	− .92	.....	+ .09	.....	2.0 West
	181	0.7	− .89	.....	+ .05	.....	2.6 "
Krüger 60	171A	1.0	− .92	.....	+ .01	+ .03	2.2 West
	182	0.6	− .90	.....	− .02	+ .06	2.8 "

It should be remarked that our final parallaxes are practically independent of the effect that we are discussing. Solutions were made from which the plates taken in the unusual position of the telescope were excluded, and preference was given to these latter results in the two cases where the parallaxes differed from each

other by more than a few thousandths of a second. The results for these five stars are summarized below.

Star	Solution from All the Plates	Solution without "Telescope East" Plates	Adopted Parallax
Weisse I, 17h322	+".113	+".150	+".140
P.M. 2164	+.282	+.276	+.282
Lamont 18180	+.051	+.065	+.060
Groombridge 3689	+.041	+.046	+.041
Krüger 60	+.252	+.259	+.252

Whether this effect is directly due to the reversal of the objective, or whether it is an hour-angle error, the present data cannot decide. This is a matter of little importance in the present connection, but it would be of general interest to make a special investigation as to this pont. For this purpose, plates in the two positions would best be secured in rapid succession on the same night.

Returning now to Table IV, let us consider the last column, which contains the probable error of one plate, or more properly that which corresponds to unit weight. These were computed from the full material without rejecting a single plate, although in one or two instances the omission of one of the plates would have reduced the probable error for that region by as much as 50 per cent. The diversity in these probable errors for different stars is not altogether accidental: it depends, for one thing, upon the brightness of the parallax star. The truth of this statement is well brought out in Table VIII, where the stars are arranged in the order of the "relative diameter of the parallax star." This quantity was computed by subtracting from the diameter of the parallax star the sum of the products formed by multiplying the diameter of each comparison star by its dependence. The data necessary to this computation are given above in connection with the comparison stars for each region. Where a plus sign is affixed to this relative diameter, the parallax star is brighter than the mean of the comparison stars. Table VIII includes (in italics) those stars for which the rotating disk was used; but, for reasons that will appear presently, it does not include probable errors in declination.

The table shows a progressive decrease in accuracy for the brighter parallax stars. The mean of all twenty-eight probable errors is ±0".0260. The mean of the first fourteen (for each of

which the parallax star is about as bright as the comparison stars) is only ±0″.0184; while for the last fourteen (for which the parallax star is considerably brighter than the comparison stars) the mean is ±0″.0336. Other things being equal, the latter group would require three times as many plates to produce parallaxes of the same degree of accuracy as for the former group.

TABLE VIII

RELATION BETWEEN THE BRIGHTNESS OF THE PARALLAX STAR AND THE PROBABLE ERROR IN RIGHT ASCENSION OR IN LONGITUDE

Star	Relative Diameter of the Parallax Star	Probable Error	Star	Relative Diameter of the Parallax Star	Probable Error
Groombridge 34 (comp.)	−0.26	±″.019	*Lamont 18180*.....	+0.45	±″.027
P.M. 2164 (fol.).....	− .23	19	*Fedorenko 2544*.....	+ .50	27
S Monocerotis.....	− .12	22	*Lalande 46650*.....	+ .53	21
Krüger 60.....	− .11	18	*Weisse 17h 322*.....	+ .64	32
31 b Aquilae.....	− .09	21	*Groombridge 3689* ...	+ .67	31
ψ Orionis.....	− .08	29	*Lalande 5761*.....	+ .72	46
μ Cassiopeiae.....	+ .03	19	*Lalande 13427*.....	+ .74	22
c Persei.....	+ .05	16	*Weisse I, 5h 952*.....	+ .74	27
π⁴ Orionis.....	+ .06	14	*Lalande 23917*.....	+ .78	28
Lalande 7443.....	+ .17	25	*Lalande 39866*.....	+ .79	33
Berlin A. 4999.....	+ .19	20	*Groombridge 34*.....	+ .79	40
P.M. 2164 (prec.)....	+ .23	14	*Lalande 15290*.....	+ .91	42
Lamont 18816.....	+ .35	10	*Fedorenko 1458*.....	+ .92	50
Lalande 25372.....	+ .37	12	*Fedorenko 1457*.....	+ .95	44

If we take the mean of the probable errors that relate to the six stars for which the rotating disk was employed to reduce the brightness of the parallax star, we obtain ±0″.0202. It appears then that *measurements upon images whose diameters have been reduced by the use of the disk are practically as accurate as those made upon correspondingly faint stars.*

In the present work I have used the disk only for those cases for which a reduction in the brightness of the parallax star was necessary in order to make its image measurable. But in the light of present experience I should, for similar work in the future, use the disk in almost every case; whenever, in fact, the parallax star exceeds the comparison stars in brightness by more than half a magnitude. Under these circumstances the probable error of one good plate secured with this telescope will be about ±0″.02, and thirteen plates of average quality should yield a value of the parallax with a probable error of ±0″.01.

It is of interest to ascertain to what is due the progressive increase of probable errors with brightness. The results for the declination measures enable us to answer this question with considerable certainty. In Table IX the probable errors for such measures are contrasted with those for right ascensions of the same stars. We see that so long as the parallax star does not differ much in brightness from the comparison stars, the measurements in the two co-ordinates are about equally accurate. But when the parallax star is considerably brighter (as is the case for each of the last six regions in Table IX), the probable error in declination is considerably smaller than that in right ascension, the two means being ±0″.0243 and ±0″.0335. The progressive increase noted in Table VIII can therefore be due only in small part to greater uncertainty in bisecting larger images, since this uncertainty applies equally to both co-ordinates. The true explanation is doubtless to be found in the guiding error, which depends upon the brightness of the image, and which will be greater in right ascension than in declination, since in the former direction the observer must contend with irregularities in the driving train in addition to atmospheric fluctuations. We have here another indication of the importance of guiding error in work of this character and the value of the rotating disk in keeping down to a minimum both accidental and systematic errors.

TABLE IX

PROBABLE ERRORS IN DECLINATION COMPARED WITH THOSE IN RIGHT ASCENSION

STAR	RELATIVE DIAMETER OF THE PARALLAX STAR	PROBABLE ERRORS	
		Right Ascension	Declination
P.M. 2164 (fol.)	−0.23	±0″.019	±0″.020
Krüger 60	− .11	18	14
P.M. 2164 (prec.)	+ .23	14	13
Fedorenko 2544	+ .50	27	22
Lalande 46650	+ .53	21	22
Groombridge 3689	+ .67	31	21
Lalande 23017	+ .78	28	29
Fedorenko 1458	+ .92	50	25
Fedorenko 1457	+ .95	44	27

ALLEGHENY OBSERVATORY
April 1911

THE EFFECT OF PRESSURE UPON ELECTRIC FURNACE SPECTRA[1]

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The effect of high pressure around the light-source in displacing the spectrum lines given by the arc and spark has been studied to such an extent that the general phenomena are well known. Measurements of the shift of lines for arc spectra through a considerable range of pressures and for a number of elements have been published by Humphreys[2] and by Duffield.[3] The effect of pressure upon electric furnace spectra is a new field, involving some phenomena peculiar to the apparatus.

The electric resistance furnace in the Pasadena laboratory was described by the writer[4] at the time of its construction and has since been used extensively in the study of the effect of varying temperatures upon spectra. The furnace chamber was built for high pressures, having been tested hydraulically to 5000 lbs. per square inch. A series of experiments has been made recently to observe the effect of pressure on the furnace spectrum, and although the work has been entirely in the nature of a preliminary survey, the results show clearly what is to be expected from the apparatus in this line of research.

EXPERIMENTAL METHOD

1. *The furnace.*—The furnace was used for this investigation with only slight changes. The tubes of Acheson graphite used at first were 30.5 cm long, 12.5 mm inside diameter and 18.5 mm outside diameter. In later experiments resistance tubes of the same length and inside diameter but of 19.5 mm outside diameter

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 53.

[2] *Astrophysical Journal*, **26**, 18, 1907.

[3] *Philosophical Transactions of the Royal Society of London*, A, **208**, 111, 1908; **209**, 205, 1908; **211**, 33, 1911.

[4] *Contributions from the Mount Wilson Solar Observatory*, No. 28; *Astrophysical Journal*, **28**, 300, 1908.

were used. A length of 38 mm at each end of the tube was clamped in the vertical graphite blocks which connected the ends of the tube with the water-cooled copper pipes carrying the current. The heated portion of the tube between the contact blocks was then 22.9 cm long. This portion was protected first by a graphite tube of 32 mm inside diameter to provide a clear space immediately about the heated tube, then by carborundum powder heaped around the outer tube to serve as a heat jacket.

The pressure-chamber was modified only by the use of conical glass windows 21.5 mm thick in the water-cooled window-holders, and by simple connections for the gas tank and gauges to one of the holes in the head of the furnace chamber, while a valve with connection for rubber tube was screwed into the other hole. Two gauges were used on the apparatus, one hydraulic, the other a low-reading gas pressure gauge. After allowing for the difference of one atmosphere in their scales, the gauges always agreed in their readings within 5 pounds.

When ready for use, a vacuum pump was connected to the valve last mentioned, and the furnace with connecting tubes was pumped out to less than 1 cm of mercury. A potential of 15 volts A.C. gave an initial current of about 900 amperes with the thinner tubes described above, and 1000 to 1100 amperes with the thicker ones. The current would quickly fall 50 amperes or more as the tube heated, then very slowly if there was no opportunity for oxidation. A photograph taken under these conditions gave the first part of the comparison for a pressure exposure. On the completion of this preliminary exposure, the outlet valve was closed, the vacuum pump disconnected, and the chamber filled with gas to the desired pressure. The furnace is almost perfectly air tight, so that the pressure of the gas would rise rapidly from contact with the heated parts within. To prevent this, the outlet valve was either frequently opened or set so as to give a constant leak sufficient to counteract the increase of pressure within. At the conclusion of the pressure exposure, the valve was opened and the gas reduced to atmospheric pressure, after which the vacuum pump was again connected and the furnace pumped out for the second portion of the comparison photograph.

2. *The optical system.*—The photographs were made with the 30-ft. (9.1 m) vertical Littrow spectrograph. The grating used was ruled by Michelson, and has a ruled surface 19 cm wide, with 500 lines per mm. The second-order spectrum was used, giving a scale of about 0.95 Å per mm. The light from the furnace was focused on the slit by means of a simple lens 10 cm in diameter and of 60 cm focal length. The position of this lens was so adjusted that the grating was centrally illuminated by a beam of light about twice the diameter of the 20 cm objective of the spectrograph. The method of making comparison exposures was to leave all parts of the optical system absolutely untouched between exposures, except for a moving of the sliding occulting plate above the slit, which is supported independently of the latter. The first comparison exposure in vacuum was made with the plate so adjusted as to give two narrow strips of spectrum. The pressure exposure was then placed between these. For the second exposure in vacuum the plate was moved back to its first position with its two openings adjusted to give longer strips of spectrum. The comparison spectrum was thus made up of the superposition of exposures taken before and after the pressure photograph, with the lines due to the second exposure usually extending a little beyond the superposed portion. The slightest instrumental disturbance was then shown by the imperfect coincidence of the comparison lines.

The furnace with the optical system as described gives a minimum risk of instrumental disturbance, since there need not be the least movement of anything which can affect the direction of the beam of light. The furnace supplies its own comparison spectrum, and this being taken in vacuum, the pressure-effect is that due to the total pressure, not to the excess of the furnace pressure above one atmosphere.

THE GAS USED, AND SPECIAL PHENOMENA

For these preliminary observations, commercial carbon dioxide in cylinders was employed, being the most easily obtained of any gas which would serve. Compressed air is out of the question for furnace work, as the large supply of oxygen would cause the furnace tube to be quickly consumed. Considerable oxidation has resulted

from the use of carbon dioxide, as the gas dissociates from contact with the hot tube and the surrounding jacket, which is raised to red heat for a considerable distance from the tube itself. The free oxygen given off causes the tube to wear thin near its ends, where the gas comes most freely in contact with the graphite. More serious than the wearing of the tube is the formation of a white smoke, probably an oxide, which becomes rather thick at high pressure and weakens the light by collecting in the end of the furnace tube as well as in the steel chamber, where it deposits on the cool metal parts as a white powder. This probably results from the contact of carbon dioxide with the heated carborundum, which is the most efficient jacketing material thus far found for the regular use of the furnace. The formation of white vapor increases with the pressure and sets a limit to the effective use of carbon dioxide. Some other material for heat insulation, combined perhaps with the use of compressed hydrogen, may give an improvement in this direction.

Two refraction effects are noticeable. One is a trembling of the image of the interior of the tube as projected on the slit of the spectrograph. This increases with the pressure, but is not disturbing at moderate pressures. The other is an interesting bending of the beam of light within the furnace owing to the fact that the gas in the lower half of the chamber is cooler than that above, there being a length of about 20 cm of compressed gas between the end of the tube and the window with the arrangement thus far used. The image on the slit was moved about 3 mm when the chamber was filled to 9 atmospheres and in the direction to be expected according to this explanation. The effect decreases after the furnace has been heated some time and the gas has become of more uniform temperature throughout. As the image on the slit is over 1 cm in diameter, there is no difficulty in adjusting at the beginning so as to allow for this movement. The effect cannot influence the pressure results, as it amounts only to taking the light from a slightly different part of the cross-section of the tube. There is no appreciable change either in intensity or wave-length of the lines given by different portions of the cross-section, as the stigmatic action of the Littrow spectrograph readily shows.

The temperature of the furnace was regulated by the impressed voltage to give a large number of lines without strong continuous spectrum, the effect of a very high temperature being to widen the lines and the reversals and eventually to give all lines in absorption when the continuous spectrum became strong enough.

Temperature measurements were made during the production of both the pressure and the comparison spectra, a Wanner pyrometer being sighted on the interior of the furnace tube through the window opposite to that directed at the spectrograph.

Pyrometer readings are made to best advantage when a graphite plug is placed midway in the tube, which gives a close approach to black body conditions; but this is impracticable when observations of the spectrum are being made. The pyrometer recorded temperatures ranging from 2100° to 2300° C. under the regular conditions of operation. There was always a close agreement between the temperature readings with and without pressure for the same current through the tube, so long as the light from the furnace was not weakened by smoke during the operation under pressure.

RESULTS

1. *Nature of pressure-effect for the furnace.*—Pressure in the furnace as high as 9 atmospheres gives a clear displacement of all lines toward the red, the magnitude of the displacement varying greatly for different lines. The general effect is a widening combined with displacement, the degree of widening also being very different for different lines and having no apparent relation to the amount of displacement. It has been noted in previous publications that the furnace, as regularly used in vacuum, does not give strong widening except for a few lines, generally those appearing in low-temperature flames, for which the amount of vapor present seems to govern the width. With pressure, however, the furnace not only gives this class of lines enormously widened, usually beyond the possibility of close measurement, but the widening extends to a second class of lines, requiring higher temperature than the first mentioned though appearing at the lower furnace temperatures (usually under 2000° C.). Such lines are always strong with the furnace in vacuum,

though not greatly widened. They appear in the high-temperature flames and in the outer vapors of the arc. The effect of pressure upon these lines is to give very strong widening, usually combined with reversal, since the lines are also given by the cooler vapor near the ends of the furnace tube. The reversals are quite or very nearly symmetrical, indicating that the displacing effect of pressure upon the cooler vapor is the same as upon the hotter. These widened lines in the spectra thus far examined never show the largest shifts. As a rule the displacement is of medium amount, but sometimes is very small.

Lines which appear at the higher furnace temperatures show various degrees of widening, though never so large as the lines just discussed, and a very great variety of displacements. The largest shifts occur for such lines. As a rule they appear unreversed and moderately widened as compared with their condition with the furnace in vacuum. Sometimes the effect of pressure is almost or entirely to blot out a line. In most cases I think this is due to a rather strong widening of a weak line, since generally a very hazy trace of the line can be seen in the pressure photograph. No clear case has been observed of a line being rendered visible by pressure when the photograph without pressure was taken at about the same temperature and normally exposed. The effect of pressure appears to be confined to a widening and displacing of such lines as are brought out by the temperature employed.

The quality of the furnace lines for measurement is in general good, perhaps better than is usually given by the arc under pressure. The reversals are well defined and generally narrow. If the exposure is not greatly prolonged, the conditions of the furnace can be controlled more closely than probably is possible for any other source.

2. *Comparison with pressure results for the arc.*—The portion of the iron spectrum from λ 4060 to λ 4460 photographed with the furnace under pressure has been studied by Duffield[1] with the pressure arc, and a comparison with his results has led to two interesting conclusions. The measurements of furnace pressure plates showed that the displacements for the majority of the lines

[1] *Philosophical Transactions of the Royal Society of London*, A, **208**, 111, 1908.

fall into three groups for which the ratio of the shifts is 1:2:4. The same relation, and in general for the same lines, was found by Duffield for the arc displacements. The good quality of the furnace lines for measurement gives this grouping very distinctly. Without any decided exception thus far observed, the relative displacements for furnace lines follow closely those for the arc. This is for two sources which have a considerable difference in temperature and which are shown by other effects to have the luminous vapor in a very different condition as regards response to the displacing influence of pressure.

The second important result in the comparison with the arc shows that *for the same pressure the furnace displacements are much larger than those of the arc.* This was established by a series of plates taken at 8 and 9 atmospheres total pressure, the magnitude of the shifts being found to run about 100 per cent larger than those given by Duffield for the same lines at 11 atmospheres and to agree closely with the arc displacements for 21 atmospheres. The superposition of the comparison spectra taken before and after the pressure exposure showed freedom from instrumental disturbance, and the relation was further shown decisively by the grouping of displacements in the 1:2:4 ratio mentioned in the preceding paragraph. An instrumental displacement of all lines would be added to the true shifts, and with the values observed for 9 atmospheres the 1:2:4 ratio would not hold even approximately.

The later measurements by Humphreys[1] of arc displacements for iron do not go lower than 42 atmospheres, but the shifts recorded are found to be in general rather less than twice those given by the furnace at 9 atmospheres, so that there is a fair agreement.

Table I gives the furnace displacements in thousandths of an Ångström unit measured on the best plate (F 140) taken at 9 atmospheres total pressure, the comparison spectrum being with the furnace in vacuum. The measurements of this plate were fully checked by four other good plates taken under the same pressure conditions. In the third and fourth columns are measurements for the same lines by Duffield at 21, and by Humphreys at 42 atmospheres. Two sets of measurements are given by Duffield, and

[1] *Op. cit.*

TABLE I

PRESSURE DISPLACEMENTS

Iron

λ	Furnace 9 Atm.	Arc, 21 Atm. (Duffield)	Arc, 42 Atm. (Humphreys)	Remarks
4063.759....	0.064	0.062	0.107	Reversed
4071.908....	0.060	0.067	0.092	Reversed
4100.901....	0.028	.....	.....	
4132.235....	0.102?	0.064	0.105	Reversed. Measurement disturbed by close blend with *V* line
4134.840....	n.m.	0.032	.....	Much weakened by pressure. Small displacement
4143.572....	n.m.	0.060	.....	Faint. Medium displacement
4144.038....	0.065	0.068	0.116	Reversed
4147.836....	0.058	.....	.....	
4152.343....	0.041	.....	.....	
4154.667....	n.m.	0.054	.....	Faint. Medium displacement
4156.970....	n.m.	0.054	.....	Faint. Medium displacement
4172.296....	0.099	.....	.....	Much widened
4172.923....	0.044	.....	0.140	
4174.095....	0.030	.....	.....	
4175.082....	0.034	.....	.....	
4177.698....	0.037	.....	.....	
4181.919....	0.085	0.043	.....	Faint
4185.058....	n.m.	.....	0.040	Faint. Medium displacement
4187.204....	0.111	0.128	.....	
4187.943....	0.114	0.094	.....	
4191.595....	0.119	0.271	.....	
4198.494....	0.125	0.127	.....	
4199.267....	0.026	0.043	0.073	
4200.148....	0.039	.....	.....	
4202.198....	0.062	0.044	0.071	Reversed
4206.862....	0.033	.....	.....	
4210.494....	0.113	0.142	.....	
4216.351....	0.033	.....	.....	Reversed
4222.382....	0.106	0.265	.....	
4232.887....	0.027	.....	.....	
4233.772....	0.101	0.107	0.240	
4236.112....	0.119	0.125	0.274	
4250.287....	0.126	0.083	.....	
4250.945....	0.060	0.057	0.089	Reversed
4258.477....	0.035	.....	.....	
4260.640....	0.124	0.124	0.246	
4271.325....	n.m.	0.075	.....	Weakened. Blend with wide reversal of 4271.934
4271.934....	0.063	0.064	0.083	Reversed
4282.565....	0.039	0.032	0.043	
4291.630....	0.030	.....	.....	
4294.301....	0.063	0.050	0.084	Reversed
4299.410....	0.126	0.126	.....	
4306.078....	0.075	.....	.....	
4308.081....	0.055	0.063	0.090	Reversed
4315.262....	0.042	0.041	0.036	
4325.939....	0.064	0.062	0.097	Reversed
4337.216....	0.062	0.069	0.090	
4347.403....	0.035	.....	.....	

TABLE I—*Continued*

Å	Furnace 9 Atm.	Arc, 21 Atm. (Duffield)	Arc, 42 Atm. (Humphreys)	Remarks
4352.908....	0.049	0.048	0.052	
4376.107....	0.032	0.032	0.039	Reversed
4383.720....	0.068	0.070	0.125	Reversed
4389.413....	0.028	.....	.....	
4404.927....	0.071	0.064	0.110	Reversed
4415.293....	0.067	0.052	0.087	Reversed
4427.482....	0.037	0.028	0.055	Reversed
4435.321....	0.032	.....	.....	
4442.510....	0.097	0.101	0.190	
4443.365....	n.m.	0.047	0.060	Faint. Medium Displacement
4447.892....	0.107	0.121	0.180	
4459.301....	0.096	0.116	0.160	
4461.818....	0.049	0.045	0.060	Reversed
5143.111....	0.057	.....	.....	
5151.020....	0.067	.....	.....	
5152.087....	0.061	.....	.....	
5166.454....	0.033	.....	.....	
5167.678....	0.051	.....	.....	Reversed
5169.069....	0.051	.....	.....	
5171.778....	0.052	.....	0.075	
5195.113....	0.256	.....	0.080	
5216.437....	0.037	.....	.....	
5225.695....	0.021	.....	.....	
5227.362....	0.052	.....	.....	
5233.122....	0.160	.....	.....	Weak and diffuse
5247.229....	0.055	.....	.....	
5250.385....	0.024	.....	.....	
5250.817....	0.113	.....	.....	Faint
5255.121....	0.029	.....	.....	
5266.738....	0.169	.....	.....	Faint
5269.723....	0.056	.....	0.083	Reversed
5270.558....	0.064	.....	.....	
5283.802....	0.083	.....	.....	Faint
5324.373....	n.m.	.....	.....	Much weakened. Large displacement
5328.236....	0.062	.....	0.100	Reversed
5328.696....	n.m.	.....	.....	Blend with reversal of 5328.236
5333.089....	0.051	.....	.....	
5341.213....	0.057	.....	.....	
5371.734....	0.068	.....	0.095	Reversed
5397.344....	0.060	.....	0.080	Reversed
5405.989....	0.051	.....	0.100	Reversed
5429.911....	0.059	.....	0.085	Reversed
5434.740....	0.057	.....	0.120	Reversed
5447.130....	0.068	.....	0.095	Reversed
5455.834....	0.065	.....	0.105	Reversed
5497.735....	0.063	.....	0.110	
5501.683....	0.060	.....	0.095	
5507.000....	0.062	.....	0.120	

Chromium

λ	Furnace, 9 Atm.	Humphreys, 42 Atm.
4254.505	0.037	0.056
4274.958	0.056	0.076
4289.885	0.048	0.087

Vanadium

λ	Furnace, 9 Atm.	λ	Furnace, 9 Atm.
4099.941	0.046	4384.873	0.067
4105.318	0.062	4390.149	0.061
4109.95	0.042	4395.413	0.065
4111.940	0.067	4400.738	0.044
4115.330	0.056	4406.810	0.067
4128.251	0.042	4407.810	0.064
4134.589	0.025	4408.364	0.059
4330.189	0.037	4408.683	0.063
4332.988	0.046	4459.922	0.061
4341.167	0.048	4460.389	0.064
4379.396	0.066		

where these are very different for a certain line the value was used which most nearly accords with a linear relation between pressure and displacement.

The measurements for the region from λ 5143 to λ 5507 were made from a very good plate (F 141) taken under conditions as nearly identical as possible with those for the previous plate in the blue region. This is the only plate thus far taken in the green with the furnace under pressure, as it was highly satisfactory. The experiments have been concentrated on the blue region because of the great variety of displacements present there and the opportunity to compare with the arc results. There is every reason to believe that the displacements measured for the two parts of the spectrum correspond to the same furnace conditions. Values for the arc displacements of the green lines as measured by Humphreys for 42 atmospheres are given in a separate column.

The three strong blue lines of chromium were measured and the displacements are entered with the arc values of Humphreys, the ratio of furnace and arc shifts being about the same as for iron.

The iron filings used in the furnace proved to contain enough vanadium to give the stronger lines of this substance, which are

accordingly listed, as measurements for this element are very scanty.

The remarks in the last column refer to the appearance of the furnace lines under pressure. The letters "n.m." denote that the line was not measurable in the pressure spectrum, but enough could be seen to give an estimate of the order of magnitude of the displacement, which is entered in the "remarks" column. The wavelengths are on the Rowland scale.

The plates were measured with a small Gaertner comparator by Miss Griffin and myself. The quality of most of the lines was such that separate sets of measurements agreed to within 0.01 Å.

Nearly all of the furnace lines for iron between λ 4060 and λ 4460 fall into three groups, for which the mean displacements show a close approach to the 1:2:4 ratio, as shown by Table II.

TABLE II

GROUPING OF FURNACE DISPLACEMENTS

Group	No. Lines	Mean Displacement
I	20	0.034
II	15	0.064
III	15	0.112
Intermediate	2	0.049

A comparison, in Table III, of the mean displacements of those lines common to my tables and those of Duffield shows the close correspondence between the grouping for the furnace and the arc.

TABLE III

MEAN DISPLACEMENTS FOR FURNACE AND ARC

Group	No. Lines	Furnace	Arc
I	5	0.035	0.035
II	13	0.064	0.061
III	14	0.113	0.138
Intermediate	2	0.049	0.047

3. *Anomalous displacements under special conditions.*—The photographs thus far discussed were taken with the furnace in vacuum for the comparison spectrum and at a pressure which gave displacements of considerable size without introducing dis-

turbing conditions. It appeared possible to reproduce at will the shifts given under these conditions, only one plate, of poor quality, showing any appreciable discordance with the set thus taken.

A variation of conditions, however, has shown that the displacements for the furnace do not depend entirely upon the pressure, but may be influenced by the state of the vapor in the furnace tube in a way which at present is not clear.

The use of a pressure above 9 atmospheres or the presence of carbon dioxide at atmospheric pressure during the preliminary comparison exposure gives in either case a large increase in the white smoke previously referred to. Pressure photographs have then occasionally given displacements larger or smaller than those normally obtained. The most striking instance of this kind was a plate taken with carbon dioxide at atmospheric pressure during the comparison exposure, then with the pressure raised to 9 atmospheres above atmospheric pressure, instead of to 8 atmospheres as was usual for the best plates when the comparison was taken in vacuum. On this plate the shifts were almost twice as large as those given normally by the same difference in pressure with the comparison in vacuum, therefore about four times as large as for the arc at equal pressure. The plate was apparently free from instrumental disturbance and the ratio of 1:2:4 for different lines held as before. Several attempts were made to obtain these large displacements again, but the conditions could not be kept uniform for different runs as they can with the furnace in vacuum, and the smoke usually gave underexposure. One fairly good plate taken in this way gave shifts very close to those regularly obtained for 9 atmospheres with the comparison in vacuum. Another anomalous plate was taken for 11 atmospheres total pressure, the comparison being in vacuum. For this plate the shifts agreed closely with those of the arc for 11 atmospheres, being about half as large as the furnace usually gave for 9 atmospheres. An attempt to repeat this plate gave displacements of the magnitude to be expected for 11 atmospheres, being a little greater than normally obtained for 9 with the furnace.

4. *Influence of temperature and vapor-density.*—The effect of difference of temperature was tested by a plate for a total pressure

of 9 atmospheres with a temperature, as read by the Wanner pyrometer, about 300° higher than that regularly employed. The difference was probably considerably greater than this, as the increased amount of smoke in the furnace due to the high temperature tended to reduce the reading. In spite of weakening of the light from this cause, the exposure for a strong photograph was only one-third of that required for the lower temperature. The high temperature photograph gave displacements consistently 10 to 25 per cent smaller than those for the temperature regularly used.

A photograph taken under the usual conditions but with a very little iron in the tube gave displacements of about the usual magnitude, though the lines were faint and poor for measurement.

These results will be taken up later in the discussion.

5. *Evidence on the linear relation between displacement and pressure.*—The proportionality between pressure and displacement has not been fairly tested with the furnace, as a much greater range of pressures is required than has been used as yet. However, a comparison is given in Table IV for the displacements of a number of good lines measured for 6, 8, 9, and 11 atmospheres, the comparison spectra being always taken in vacuum. A regular increase is evident, indicating that a linear relation probably holds if the conditions of the furnace are properly controlled.

TABLE IV

CHANGE OF DISPLACEMENT WITH PRESSURE FOR SELECTED LINES OF IRON

A	DISPLACEMENTS			
	6 Atm.	8 Atm.	9 Atm.	11 Atm.
4250.945.....	0.048	0.051	0.060	.....
4271.934.....	.038	.061	.063	0.082
4308.081.....	.040	.044	.055	.076
4325.939.....	.033	.057	.064	.070
4376.107.....	.018	.031	.032	.037
4383.720.....	.034	.051	.068	.071
4404.927.....	.042	.052	.071	.075
4415.293.....	.023	.058	.067	.064
4427.482.....	.023	.030	.037	.037

6. *Data concerning the relation between pressure-displacement and Zeeman separation.*—A comparison of the pressure-effect with the

magnetic separation for lines of the iron spectrum was given in a former paper,[1] using the pressure measurements of Humphreys and Duffield. The furnace material enables us to compare the average displacements and separations for two regions of the spectrum about 1000 Ångström units apart. The average displacement for the total number of lines in the two regions cannot be compared with fairness at present, as most of the weaker lines in the green were too faint for the measurement of their displacements and the largest pressure-effects usually occur among lines of this class. With the available material it seemed best to select lines showing a similar behavior in laboratory sources, as these probably arise from vibrating particles having at least some points of similarity. Such lines are those which appear at low temperatures of the furnace and reverse easily. Fifteen lines of this character are included in the region from λ 4050 to λ 4450 given in Table I, and 9 lines between λ 5050 and λ 5450, excluding λ 5434.740, which is not comparable, being unaffected by the magnetic field. Assuming that the pressure plates were taken under similar conditions, we see that the displacements of these lines show no tendency to change with the wave-length, the mean shift being 0.058 for the blue and 0.060 for the green lines. (The very close agreement is of course largely accidental.) The magnetic separations for these lines, however, show a decided increase with the wave-length, although the separations of the lines in each region are of the same order of magnitude. For a field-strength of 16,000 gausses, the mean separation of the 15 blue lines given as "reversed" in Table I is 0.330, while that for the 9 green lines is 0.520, an increase of 60 per cent for a difference of wave-length of about 1000 units. This affords further evidence against a close connection between the phenomena of pressure and of the magnetic field.

7. *The adaptability of the furnace to pressure investigations.*— While it is too early to state definitely the limitations of the furnace as a pressure source, a few points may be noted as to the relative usefulness of the furnace and arc in this line of work. In the total number of lines produced under pressure, there is little to choose

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 46; *Astrophysical Journal*, **31**, 433, 1910.

between them. The tables for iron given by Duffield and in the present paper contain almost exactly the same number of lines for the same range of wave-length, though the lists are not identical owing to the difference in relative intensity of lines given by the furnace and arc. Nineteen lines measured by Duffield could not be measured on the furnace plates, while values for 18 furnace lines are given which do not appear in the arc tables. In the green region, measurements are given for almost double the number of lines measured by Humphreys in the arc, though probably the high pressure used by him increased the difficulty in obtaining the weaker lines.

As to quality, a line clearly and narrowly reversed given by any source usually admits of close measurement. I believe experience will prove that unreversed lines can be measured to better advantage on furnace plates, as there seems to be less tendency toward strong and unsymmetrical widening than is usually given by the arc.

The arc will have an advantage over the furnace in the production of the enhanced lines of some elements, such as titanium, in which most of the lines characteristic of the spark are given of moderate intensity by the arc.

For very high pressures the arc may be more efficient than the furnace, though this is by no means certain, since these preliminary experiments have suggested a large variety of ways in which present difficulties may be overcome. The use of a different compressed gas, different jacketing material, and probably shorter tubes should permit the use of much higher pressures. The relative displacements of lines have been given clearly by the pressures thus far employed.

The chief usefulness of the furnace for pressure work will probably occur when it is desirable to take advantage of the special conditions of radiation afforded by it. The present work has shown that its results may give large differences from those normally obtained with the arc. When an extended investigation has shown what conditions are responsible for these differences, the close control of the state of the radiating vapor which is possible with the furnace will probably open lines of work which cannot be carried out to advantage with any other source.

In astrophysical problems the temperatures involved are high, being approached best by the arc and spark; but in other respects the state of the luminous vapor resembles more nearly that of the furnace, so that certain phases of the pressure phenomena can be studied to best advantage by means of this source.

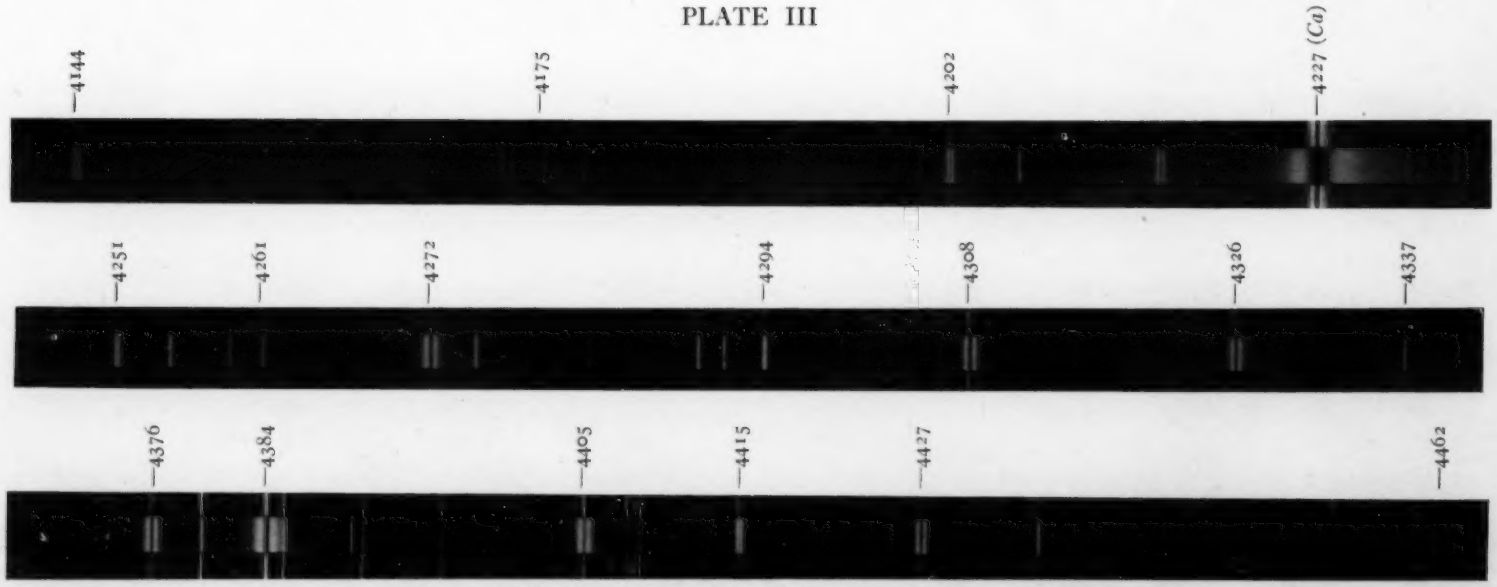
8. *Explanation of the plates.*—Plates III and IV present enlargements of the more interesting regions of the iron spectrum covered by the furnace plates. Certain groups of lines are favorable for the examination of the differences in relative magnitude of displacements. In Plate III, the 1:2:4 relation is represented by λ 4258.477, λ 4250.945 or λ 4271.934, and λ 4260.640 respectively. The group of reversed lines near λ 4383.720 shows this line with $\lambda\lambda$ 4404.927 and 4415.293 displaced approximately twice as much as $\lambda\lambda$ 4376.107 and 4427.482. An example of the very wide reversal of flame lines is given by λ 4227 of calcium, arising from impurities. The same degree of reversal was obtained for the three blue lines of chromium when a large amount of this metal was used in the furnace.

Plate IV shows a portion of the iron spectrum in the green. The spectrum given by the arc between iron poles is also reproduced for comparison. It is seen that the furnace under pressure gives in this region only lines which are strong and sharp in the arc. The other strong lines, with edges not so sharp, are given by the core of the arc, and appear in the furnace spectrum very faintly at the highest temperatures. The comparison spectrum for the pressure photograph shows a combination of effects owing to the fact that the second comparison exposure, taken with longer slit, ended by the tube burning through, giving during a few seconds a spectrum similar to that for the core of the arc. The result is that the regular furnace lines appear with fainter extensions, while those lines which are not usually given by the furnace show faintly and of uniform intensity throughout their length.

DISCUSSION

It has been the purpose of this paper to record the pressure-effects for the furnace as given by a definite set of experimental conditions, which as yet have been varied only to a limited degree.

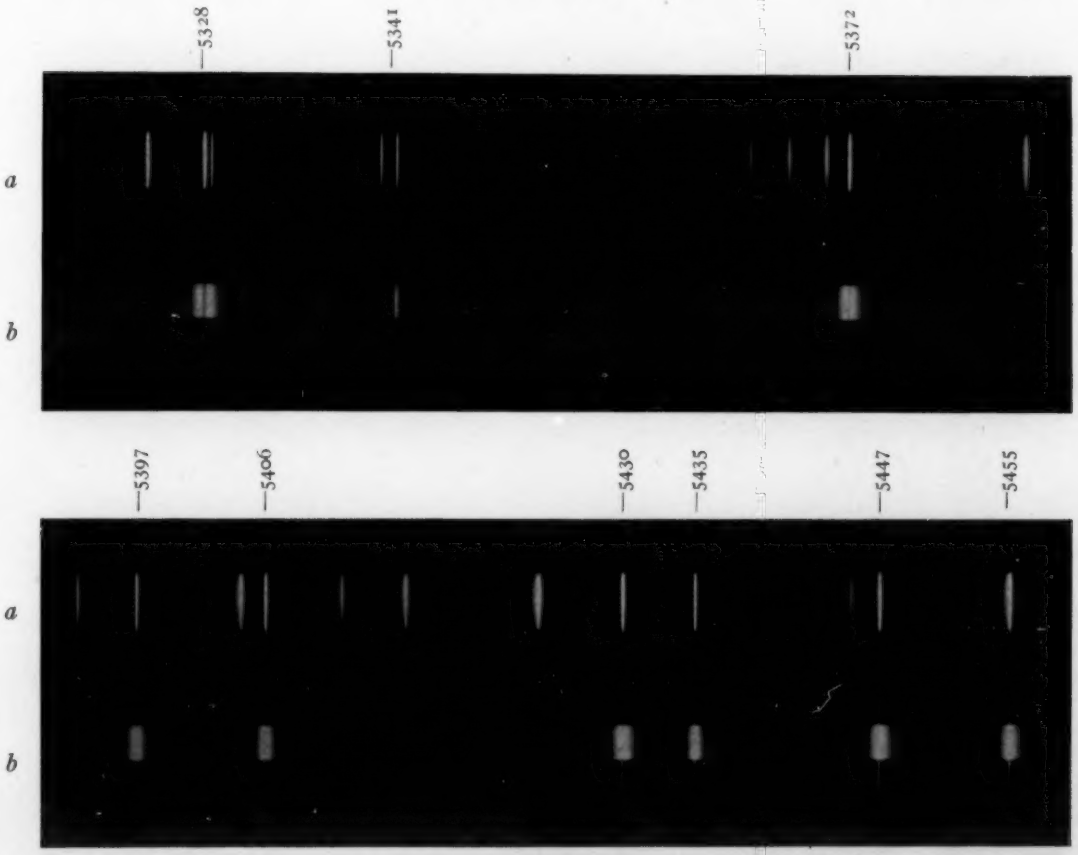
PLATE III



EFFECT OF PRESSURE ON THE ELECTRIC FURNACE SPECTRUM OF IRON

Inner portion of each spectrum given by furnace at 9 atmospheres. Comparison spectrum given by furnace in vacuum
Scale: 1 mm = 0.5 Å

PLATE IV



a, Spectrum of iron arc *b*, Effect of pressure on the electric furnace spectrum of iron

Inner portion of spectrum *b* given by furnace at 9 atmospheres

Comparison spectrum given by furnace in vacuum

Scale: 1 mm = 0.5 Å

At this time it would be merely speculative to discuss the results farther than to bring out a few leading points in the question as to why the furnace gives displacements consistently larger than those of the arc. The occasional departures from regularity in the furnace effects are to be regarded as a strengthening or weakening of a general displacing influence.

It may be noted that these results have been in a way predicted by observations on the arc under pressure. Workers with the arc have obtained many discordant results for pressures under 20 atmospheres, so that for this range it has been difficult to show a linear relation between shift and pressure. Duffield obtained a plate at 25 atmospheres which gave shifts twice as large as those which accorded with the linear relation. This is a difference of the same magnitude that the furnace at 9 atmospheres gives as compared with the arc at the same pressure. This and other departures from the linear relation observed by Duffield on certain plates were not to be explained by errors of measurement, and are considered by him as probably connected with the tendency to reverse, the reversals of lines being broader and stronger on the plates giving abnormal shifts.

The production of large displacements may arise from causes of two kinds, either or both of which may be active in the furnace. The luminous metallic vapor may be in such a condition as to weaken the resistance offered by the vibrating particle to a change in its period; or the condition of the compressed gas may enable it to exert a stronger displacing influence.

To consider first a possible weakening of the forces controlling the period, we find that the differences observed between the effects of the furnace and the arc indicate that a decrease in the internal energy of radiation, regulated in the case of the furnace by the temperature, may permit a large disturbance of the period by pressure; in other words, that lower temperature may favor large displacements. The result of the test as to the effect of increased furnace temperature showed that the difference produced was in this direction; and as there is probably an interval of at least 1200° between the lower furnace temperature and that of the arc, this might explain in large measure the differences obtained were it

not that other lines of evidence indicate that temperature difference in itself cannot fully account for the results. In the first place, those furnace plates which gave differences larger or smaller than regularly obtained were made with the furnace at about the usual temperature. Other evidence is that the reversals for lines with the furnace under pressure are symmetrical, which should not be the case if the cooler vapor near the ends of the tube gives a line of different wave-length from the vapor in the middle. A difference in the amount of iron vapor present in the furnace tube also appeared to be without decided effect.

Evidence from arc investigations may be considered in this connection. The arc under pressure rarely burns steadily, the spectrum of different regions being taken in turn under ordinary conditions. Different investigators have used a variety of arrangements of the arc, including carbon and metallic terminals and the rotating type, and if either temperature or vapor-density exerts a controlling influence, it is doubtful if results for the arc under pressure would show even as much consistency as they do.

The furnace results give little ground to choose between the theories proposed by Humphreys,[1] Richardson,[2] and Larmor[3] to account for the pressure-effect, but since that of Larmor involves the dielectric constant of the luminous vapor, a possible influence upon this quantity may be considered. An increase in the dielectric constant should diminish the elasticity of the ether about each particle of matter, with a resulting tendency toward increase of vibration period. It would seem probable that the difference between the heated vapor in the furnace and the discharge conditions of the arc might give a change in the inductive capacity, but there is little evidence as to its direction or amount. However, Baedeker[4] measured the change of dielectric constant with temperature through various ranges, sometimes as high as 150° C., of several vapors, among them sulphur dioxide, ammonia, ethyl chloride, methylene chloride, and chloroform, and found in all cases a decrease

[1] *Astrophysical Journal*, **23**, 233, 1906.

[2] *Philosophical Magazine* (6), **14**, 557, 1907.

[3] *Astrophysical Journal*, **26**, 120, 1907.

[4] *Zeitschrift für physikalische Chemie*, **36**, 305, 1901.

in the dielectric constant with increase in temperature. If this relation is general for gases and holds at very high temperatures, the temperature difference between furnace and arc would change the dielectric constant in the right direction to give larger shifts for the furnace.

We may also consider whether the effect can be ascribed to the large dielectric constant of carbon dioxide as compared to compressed air. The dielectric constant of air at 20 atmospheres was measured by Occhialini[1] as 1.0101, that for carbon dioxide at 20 atmospheres by Linde[2] as 1.025. This difference in itself should give larger displacements for the furnace in carbon dioxide than for the arc in air, although, as has been remarked by Humphreys, a change directly proportional to the dielectric constant would be within the errors of measurement. Tests have been made of the displacements given by the spark in different atmospheres by Anderson[3] and by Hale and Kent.[4] The former found some evidence of an increased displacement in carbon dioxide as compared with hydrogen. The question was discussed at some length by Humphreys,[5] but a systematic investigation of the effect of different gases under pressure for the arc and spark has not yet been made. It is hoped to make such a comparison at an early date with the furnace. The irregular displacements occasionally obtained when white oxide was present in the furnace can perhaps be most easily explained through a change of the dielectric constant.

One feature in which the furnace conditions are different from those of the arc is that the effect of the compressed gas should be more steady and possibly stronger in the furnace. Here we have the carbon dioxide heated to about the same temperature as the radiating metallic vapor, and with considerable uniformity throughout several inches of the tube, with little circulation. With the arc, the heating of the gas is very much localized, with opportunity for constant movement of the gaseous particles in and out of the heated region. The fact that in the arc the metallic particles carry

[1] *Physikalische Zeitschrift*, **6**, 669, 1905.
[2] *Annalen der Physik und Chemie*, **56**, 546, 1895.
[3] *Astrophysical Journal*, **24**, 221, 1906.
[4] *Publications of the Yerkes Observatory*, **3**, Part II, 1907.
[5] *Astrophysical Journal*, **26**, 18, 1907.

the greater part of the electric current makes it a question how nearly the thermal condition of the gas approaches that of the metallic vapor.

SUMMARY

The results obtained may be summarized as follows:

1. The furnace under pressure gives a spectrum containing practically all lines brought out by the same temperature with the furnace in vacuum.

2. The general effect of pressure is a widening of lines and displacement toward greater wave-length, the widening for low-temperature lines being very strong and usually accompanied by reversal.

3. The number of lines which are measurable is approximately the same as for the arc under pressure, with some differences due to the different relative intensity of lines in the two sources.

4. The displacements of nearly all iron lines from λ 4050 to λ 4450 fall into three groups, the ratio of the displacements being 1:2:4, which ratio was also found for these groups of lines in the arc.

5. So far as observed, the *relative* displacements of the furnace lines appear to follow closely those of the arc.

6. The *absolute* displacements of furnace lines at a pressure of 9 atmospheres are about twice those given by the arc at the same pressure and compare closely in magnitude with the arc displacements for 20 atmospheres.

7. Some furnace photographs have shown shifts larger or smaller than those usually given by the same pressure. These were apparently due to differences which evidently prevailed in the condition of the luminous vapor.

8. For iron lines of the same general character, produced at low furnace temperatures and easily reversed, the displacement shows no tendency to increase with the wave-length, the pressure-effect being in this respect very different from the effect of a magnetic field for the same lines.

I am indebted to Miss Griffin for much assistance in the measurement of the spectrograms.

MOUNT WILSON SOLAR OBSERVATORY

March 6, 1911

MOTION AND CONDITION OF CALCIUM VAPOR OVER SUN-SPOTS AND OTHER SPECIAL REGIONS.[1] I

By CHARLES E. ST. JOHN

In a former paper, "The General Circulation of the Mean and High-Level Calcium Vapor in the Solar Atmosphere,"[2] the investigation was confined to those portions of the solar disk that were free from spots and flocculi. The points at which measurements were made were 1, 12, 25, 35, 50, and 70 mm from the limb and at the center, on an image 172 mm in diameter. The investigation was continued through 12 rotations of the sun, during which period the position angle of the solar axis described nearly a complete cycle; the points selected for measurement lay along a horizontal diameter of the image produced by the Snow coelostat, and as the plates were taken at irregular intervals each point corresponded to a random distribution of positions on the solar surface but at definite distances from the center of the disk. The combined results of the measurements showed a descending motion for the absorbing vapor of 1.14 km per second, and an ascending motion for the emitting vapor of 1.97 km per second over the surface of the sun. This result, depending on some 500 positions on the solar surface, represents a mean that is practically free from the effects of causes that are occasional and diverse in their action and may be assumed to show the condition of the calcium vapor over regions of the surface not subject to great or exceptional disturbances, such as spots, flocculi, and prominences in projection.

In the present paper are presented the results of an investigation in which the measurements of the wave-lengths of the absorption line K_3 and the emission line K_2 of calcium have been extended over the umbrae and penumbrae of spots, over the accompanying flocculi and circumfloccular regions, and over some other points

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 54.

[2] *Contributions from the Mount Wilson Solar Observatory*, No. 48; *Astrophysical Journal*, **32**, 36, 1910.

where the calcium vapor showed exceptional phenomena. Measurements are given also for the intensity of the emission line in terms of the continuous spectrum and for the relative intensities of K_1, K_2, K_3, and for different points of the same line. The series of plates extends over nearly two years. The spectrographs employed are of the auto-collimating type and are described as Nos. 2 and 3 in *Contribution* No. 44.[1] In the 18-foot (5.5 m) instrument (No. 2) a 20-cm Michelson grating having 590 lines to the centimeter and a 10-cm Rowland grating having 568 lines to the centimeter were used, the scale in each case being approximately 1 mm = 1.0 Å. This instrument can be used as a section-spectrograph, and is an application of the principle of the *spectro-enregistreur des vitesses* suggested by M. Deslandres.[2] The arrangement permits one easily and rapidly to take exposures of successive points or successive exposures of the same point. The majority of plates were taken with this spectrograph, using a second slit 12 mm wide in order to include the solar standards, and 45 mm long, the maximum length of the second slit. Often successive exposures were taken over a spot, but more frequently the first slit was moved by steps of 2 mm each over the region under investigation. The other plates were taken with the 30-foot spectrograph (No. 3) used in connection with the 60-foot tower telescope in which the above-described Rowland grating was used, giving a scale of approximately 1 mm = 0.60 Å. These plates are designated by the letter "*c*."

The measurements of the spectra were made upon a Gaertner comparator reading directly to 0.001 mm. The plates were measured red right and red left, and at least four settings were made for each position. The two iron lines λ 3930 and λ 3935 were employed as standards. The solar wave-lengths of these lines were determined at the center of the sun in terms of the International Standards as described in *Contribution* No. 48, p. 42.[3] The wave-lengths of these lines at the center of the sun were found to be λ 3930.306 and λ 3935.823, the arc values being λ 3930.301

[1] *Astrophysical Journal*, **31**, 143, 1910.

[2] *Comptes Rendus*, **114**, 277, 1892.

[3] *Astrophysical Journal*, **32**, 36, 1910.

and λ 3935.818 respectively. Their wave-lengths over the surface of the sun, away from the limb, have been assumed to remain constant except in the immediate neighborhood of sun-spots where the radial motions discovered by Evershed may affect them when the slit is not placed perpendicular to the radius drawn through the spot. To eliminate any such effect it was the practice to make settings on portions of the standard lines outside the penumbral regions which are the seat of the radial motions in the reversing layer. To fix the points of the line at which measurements were to be made, and to avoid the effect that might be produced by having other portions of the line in the field of view, the photographic plate was often covered by an adjustable slide in which there was a slit 1 mm wide and sufficiently long to include the standard lines. The platform of the comparator carried a millimeter scale at each end by means of which the plate could be moved in a direction perpendicular to the screw in order to bring any desired point of the line into the field of view.

Distortions of the H and K lines of calcium are not uncommon during periods of activity and violent changes in and around sun-spots, when eruptions often take place in the immediate vicinity. Displacements of the lines occur at such times, which indicate very high velocities in the line of sight, amounting to one hundred kilometers or more per second. The measurements that form the basis of the present article were made upon plates that did not show such extreme and unusual conditions, but were representative, rather, of the more common and steady states. The purpose has been to determine what is the usual rather than the unusual, to find what are the prevailing movements of the calcium vapor in and around sun-spots, if such movements do exist in any stable form. There is undoubtedly much that is billowy, tumultuous, and apparently irregular in the movements in the upper regions of the solar atmosphere, but it is a question whether underneath the adventitious and casual there may not exist some systematic effects that point to generally acting causes. The present investigation was undertaken mainly to obtain quantitative data bearing upon this question.

TABLE I

THE K LINE OF CALCIUM OVER THE UMBRAE OF CENTRAL SPOTS

Plate	Date	Spot	On C.M.	Wave-Length of K Line	Eccentric Distance	Character	Remarks
	1908		1908		mm		
126.....	Dec. 7	6577	Dec. 8.3	3933.680 (4)	37.5	Bright, single	2d apparition. Large, regular. Returned as 6592, 6609, 6627, 6647, and 6661
138.....	Dec. 9	6577	Dec. 8.3	.679 (2)	35.0	Bright, single	Large, regular
				3933.680			
	1909		1909				
215.....	Jan. 18	6602	Jan. 19.9	.660	26.0	Bright, single	2d apparition. Large, regular. Returned as 6618
219.....	Jan. 19	6602	Jan. 19.9	.658 .655 .652 .650 .655	6.3	Bright, single	On 2 successive days this spot showed from 6 consistent measurements an upward motion over the umbra
				3933.655			
228.....	Jan. 20	6602	Jan. 19.9	.691 .690 .681 .688	14.6	Bright, single	On this, the following day, the motion was strongly downward
				3933.688			
228.....	Jan. 20	6604	Jan. 22.3	.686 (2)	41.8	Bright, single	1st apparition. Large. Regular. Returned as 6621
230.....	Jan. 23	6604	Jan. 22.3	.682 (2)	33.0	Bright, single	Large, regular
				3933.684			

237.....	1909 Jan. 28	6606	1909 Jan. 28.9	3933.675 (3)	31.0	Bright, single	Only appearance. Large, irregular cluster. Active region
247.....	Jan. 29	6606	Jan. 28.9	.676 (4)	29.0	Bright, single	Irregular cluster
				3933.676			
247.....	Jan. 29	6608	Jan. 30.3	.678 (2)	37.4	Bright, single	2d apparition. Large, irregular spot about to break up
257.....	Jan. 30	6608	Jan. 30.3	.682 (3) .665 (5)	28.0	Bright, single	Line strongly curved over umbra showing a change in motion over different parts
263.....	Jan. 30	6608	Jan. 30.3	.683 (5) .667 (1)	28.0	Bright, single	The table gives the means for the 2 parts of the line
				3833.675			
258.....	Jan. 30	6609	Feb. 1.1	.677 (4)	44.5	Bright, single	Large spot. 4th apparition. Return of 6592, a return of 6577
263.....	Jan. 30	6609	Feb. 1.1	.682 (2)	44.5	Bright, single	Large, regular
				3933.679			
290.....	Feb. 24	6625	Feb. 26.5	.693 (4)	40.0	Bright, single	1st apparition. Large, regular. Returned as 6645
296.....	Feb. 25	6625	Feb. 26.5	.685 (6)	25.2	Bright, with dark center	λ for weak absorption line 3933.684 (4)
304.....	Feb. 26	6625	Feb. 26.5	.687 (3)	27.0	Bright, with dark center	λ for weak absorption line 3933.685 (3)
309.....	Feb. 27	6625	Feb. 26.5	.694 (2)	42.4	Bright, single	Regular
				3933.689			
304.....	Feb. 26	6627	Feb. 28.5	.679 (3)	54.5	Bright, with dark center	5th apparition. Return of 6609. λ for absorption line 3933.673 (3)
309.....	Feb. 27	6627	Feb. 28.5	.678 (4)	44.0	Bright, single	Spot shows indications of breaking up
				3933.678			

TABLE I—*Continued*

Plate	Date	Spot	On C.M.	Wave-Length of K Line	Eccentric Distance	Character	Remarks
	1909		1909		mm		
439	April 24	6660	April 24.6	3933.684 (2)	C'ntr'l	Bright, single	Large, regular spot. One apparition
563	July 23	6695	July 24.4	.684 (2)	11.0	Bright, single	Large, regular spot. Leader of stream
567	July 24	6695	July 24.4	.679 (4)	10.0	Bright, single	Regular
				3933.681			
617	Oct. 20	6746	Oct. 20.7	.687 (2)	15.0	Bright, single	Large spot. 2d apparition. Returned as 6765
621	Oct. 30	6753	Oct. 31.4	.679 (2)	18.2	Bright, single	3d apparition. Large, regular spot. Line weak
624	Oct. 31	6753	Oct. 31.4	.678 (4)	C'ntr'l	Bright, single	Line weak
				3933.678			
649*a*	Nov. 6	6756	Nov. 6.4	.682 (2)	19.0	Bright, single	Large, regular. 2d apparition. Leader of train. Returned as 6778
649*b*	Nov. 6	6756	Nov. 6.4	.686 (3)	19.0	Bright, single	Regular
				3933.685			
651	Nov. 15	6765	Nov. 17.0	.674 (3)	27.5	Bright, single	3d apparition. Return of 6746
652	Nov. 16	6765	Nov. 17.0	.671 (1)	17.4	Bright, single	Regular
653	Nov. 16	6765	Nov. 17.0	.685 (3)	17.4	Bright, single	Regular
660	Nov. 17	6765	Nov. 17.0	.697 (1)	18.3	Bright, single	Regular
				3933.682			
669	Nov. 27	6771	Nov. 26.7	.687 (3)	36.0	Bright, single	1st apparition. Large, regular. Returned as 6786
674	Nov. 27	6772	Nov. 26.7	.665 (4)	21.0	Broad, bright	4th apparition. One of changing group
679	Nov. 28	6772	Nov. 26.7	.667 (2)	22.0	Broad, bright	Strong, bright line
				3933.666			

	1909		1909				
680.....	Nov. 28	6774	Nov. 27.4	3933.670 (2)	27.0	Bright, single	One of developing group
714.....	Dec. 23	6786	Dec. 24.0	.696 (6)	29.5	Bright, single	Large, regular. Return of 6771. Line weak
714.....	Dec. 24	6787	Dec. 24.9	.690 (2)	29.0	Bright, single	Large, regular. Return of 6771
716.....	Dec. 24	6787	Dec. 24.9	.693 (4)	29.0	Bright, single	Large, regular
				3933.692			
714.....	Dec. 23	6788	Dec. 25.1	.688 (2)	44.0	Bright, single	Large, regular. Return of 6774
717.....	Dec. 24	6788	Dec. 25.1	.681 (4)	27.0	Bright, single	Large, regular. K line weak
				3933.683			
	1910		1910				
76c.....	May 18	6847	May 18.6	.688 (2)	20.0	Bright, single	Regular
76c.....	May 18	6849	May 19.7	.684 (2)	19.0	Bright, single	Large, regular. Leader of stream. Shows inflow of calcium vapor on plates taken near limb
79c.....	May 19	6849	May 19.7	.691 (3)	C'ntr'l	Bright, single	Large, regular
				3933.688			
195c.....	Aug. 9	6874	Aug. 9.5	.684 (3)	C'ntr'l	Bright, single	Large, regular. Shows inflow. Terrestrial magnetic disturbances. Returned as 688o
256c.....	Sept. 27	6886	Sept. 26.9	.687 (2)	C'ntr'l	Bright, single	Large, regular. 2d apparition
296c.....	Oct. 21	6897	Oct. 21.3	.683 (2)	25.0	Bright, single	Shows inflow on plates taken near limb. At first absorption line showed even with fine seeing. Later only bright line

VERTICAL MOTION OF CALCIUM VAPOR OVER THE UMBRAE OF SPOTS

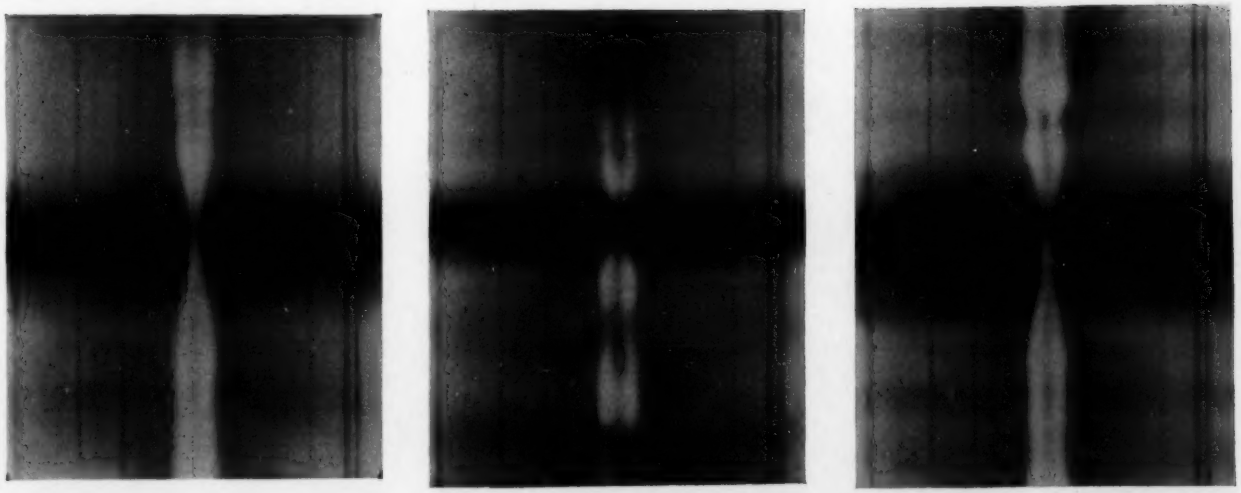
The usual appearance of the K line of calcium over spot umbrae is that of a relatively narrow but actually broad bright line, its width being approximately 0.3 Å. See Plate V (*a*). Compared with the line over the surrounding faculae it is broader than K_3 and narrower than K_2. Occasionally there is superposed upon it a narrow absorption line. This is often due doubtless to photospheric light that reaches the slit when the seeing is poor. The question whether it is ever a real spot phenomenon will be discussed later in the paper. The measurements were confined to the plates obtained when the spots were near the central meridian. The average diameter of the solar image was 170 mm. On an image of this diameter the vertical component of the motion of the rising or falling vapor at a point 35 mm from the center of the disk is about 10 per cent less than at the center. Few of the spots upon which measurements were made were so far from the center. Not all the plates were taken for this investigation, and the most available have been selected from those already on hand. Table I gives the results of the measurements. The Greenwich spot numbers are in the third column; the wave-length of the bright K line of calcium is given in the fifth column in International Units; the figures in parentheses following the wave-lengths show the number of separate measurements upon which the result depends; in the main these refer to separate exposures on the same plate. The distances of the spots in millimeters from the center of the image are given in the sixth column. In the last column under "remarks," the history and description of the spot are outlined, and the wave-lengths of the absorption line K_3 are included. The spots are arranged serially in the order of their appearance. The wave-length of the K line of calcium in the arc in International Units, to which the wave-lengths in the spots may be referred for the purpose of determining the motion of the calcium vapor, is λ 3933.667, as determined in *Contributions* No. 44, p. 10.[1]

Of the twenty-five spots studied, one, 6577, was observed at three apparitions; and four, 6746, 6771, 6772, and 6774, were observed at two apparitions. Twenty-two spots showed at all

[1] *Astrophysical Journal*, **31**, 152, 1910.

PLATE V

a *b* *c*



THE K LINE OF CALCIUM OVER SUN-SPOT NO. 6874

Enlargement: 6 times from original negatives with the 30-foot spectrograph and tower telescope

a, Normal reversal over umbra. Spot central. 1910, August 9.

b, Displacements due to inflow of penumbral vapor. Slit parallel to solar radius through spot, 17 mm from east limb. 1910, August 5.

c, Displacements due to rotation of penumbral vapor. Slit perpendicular to solar radius through spot, 23 mm from west limb. 1910, August 12.

times a downward movement of the vapor producing the bright K line of calcium. The velocity of descent varied for individual spots from 0.68 km per second in the case of 6606 to 2.2 km per second in the case of 6786, the general mean being 1.30 km per second. Spot 6602 gave some interesting results. On the first two of the three days on which observations were obtained the calcium vapor was rising with a velocity of 0.9 km per second. On the following day it was descending with a velocity of 1.6 km per second. This sudden change in the direction of the movement of the vapor was so surprising that the plates were remeasured. The results were similar, as indicated by the individual measurements given in full in the table. Spot No. 6608 was a large spot approaching dissolution. The bright calcium line over the umbra was strongly curved. The portion displaced to the violet was the brightest and the measurement indicated a possible upward velocity of the vapor of 0.15 km per second. The measurement of the portion of the line displaced to the red indicated a downward velocity of 1.22 km per second. The result given in the table for this spot is the mean, and indicates on the whole a considerably greater velocity downward than upward. The interesting fact, however, is that two parts of the umbra show these different conditions. The measurements in the case of spot 6772 point to a practically stationary state of the vapor producing the bright line, namely, an upward motion of less than 0.1 km per second. On its return as 6787 the emitting vapor was descending with a velocity of 1.9 km per second. From the large percentage (88 per cent) of the spots showing only downward movement of the emitting vapor and from the varying results for the other spots, one can conclude that in the umbrae of spots the calcium vapor is in general descending, but that under certain conditions upward motions do occur.

VERTICAL MOTION OF CALCIUM VAPOR OVER THE PENUMBRAE OF SPOTS

The usual appearance of the K line of calcium in the penumbra of a spot is very similar to that over the surrounding flocculus, consisting of the two bright components of K_2 and the central dark line K_3, except that the width of the K_2 line decreases rapidly as it

nears the umbra and the absorption line grows less distinct and finally disappears over the umbra. These two portions of the line lie, of course, upon the broad shading of K_1, which is not considered in the wave-length measurements, as it is not possible to fix its position with sufficient accuracy. Both K_2 and K_3 have been measured; the center of the bright line was obtained by adding to the wave-length of the violet component the difference of wave-length between the absorption line and the red component.[1] Upon plates taken as these were, near the center of the solar image, the line usually runs straight over flocculus, penumbra, and umbra. No correction for distance from the center has been made to the wave-lengths in Table I, but in Table II, containing the results of the measurements over the penumbrae of the spots, the data for the umbrae of the individual spots are given with such corrections, which in no case exceed 0.002 Å.

TABLE II

THE K_2 AND K_3 LINES OF CALCIUM OVER THE PENUMBRAE OF CENTRAL SPOTS

NUMBER	NORTH		UMBRA	SOUTH		REMARKS
	K_2	K_3		K_2	K_3	
6577	3933.665(5)	3933.681(5)	3933.681	3933.680(5)	3933.692(5)	2d apparition. Returned as 6592
6602	.633(2)	.661(2)	.655	.643(2)	.676(2)	For 2 days
	.658(2)	.685(2)	.688	.662(2)	.690(2)	On the following day
6604	.668(1)	.685(1)	.686	.691(1)	.686(1)	1st apparition
6606	.677(2)	.671(2)	.677	.679(1)	.668(1)	Only appearance
6608	.661(2)	.671(2)	.676	.667(2)	.678(2)	2d apparition, about to break up
6609	.657(5)	.670(5)	.681	.679(3)	.686(3)	Return of 6592
6625	.670(2)	.684(2)	.690	.666(2)	.684(2)	1st apparition. Returned as 6645
6627	.681(2)	.692(2)	.680	.659(2)	.680(2)	Return of 6609
6660	.684(4)	.685(4)	.684	.692(3)	.684(4)	Only appearance
6695	.657(1)	.674(1)	.681	.672(1)	.687(1)	Leader of stream
6746	.684(1)	.684(1)	.687	.670(1)	.686(1)	2d apparition
6753	.651(4)	.674(4)	.678	.659(4)	.674(4)	3d apparition
6756	.674(5)	.689(5)	.685	.667(5)	.680(5)	2d apparition
6765	.653(4)	.678(4)	.681	.661(4)	.675(4)	Return of 6746
6771	.658(3)	.688(4)	.688	.632(3)	.659(3)	1st apparition
6772	.653(2)	.678(2)	.666	.654(3)	.675(3)	1st apparition
6774	.661(1)	.672(1)	.670	.648(1)	.684(1)	Developing spot
6786	.680(2)	.689(2)	.697	.670(2)	.680(2)	Return of 6771
6787	.667(4)	.694(4)	.693	.659(4)	.679(4)	Return of 6771
6788	.662(4)	.673(4)	.684	.668(4)	.678(4)	Return of 6774
6847	.665(2)	.694(2)	.688	.672(2)	.683(2)	1st apparition
6849	.685(1)	.689(1)	.688	.672(1)	.681(1)	Shows inflow
6874	.681(1)	.681(1)	.684	.666(1)	.661(1)	Shows inflow and vortex
6886	.655(1)	.653(1)	.687	.666(1)	.687(1)	
6897	.674(1)	.678(1)	.683	.684(1)	.696(1)	Shows inflow
	3933.665(63)	3933.682(63)	3933.682	3933.665(57)	3933.679(57)	

[1] Adams, *Contributions from the Mount Wilson Solar Observatory*, No. 6, 3, 1905; *Astrophysical Journal*, **23**, 47, 1906.

The headings "north" and "south" are not to be taken too literally, as they refer only to opposite sides of the spots in a very general north-and-south direction. The separation into these two groups was made in order that the results of the two independent sets of measurements might serve as checks upon each other. The mean of the two surprisingly concordant results for the emitting vapor is 3933.665. The measurements are difficult to execute, but considerable reliance may be placed on the final mean, depending as it does upon 120 measurements. The wave-length in the arc being 3933.667 Å, it appears that in the penumbrae of spots the calcium vapor producing the emission line is on the average neither ascending nor descending, as the mean would imply an upward velocity of only 150 m per second. The variation in the wave-length of the K_2 line in the penumbrae of different spots is greater than the errors of measurement in some cases, and should not be left out of consideration in the discussion of the individual spots. The high-level absorbing vapor is descending with a velocity of approximately 1 km per second, if its wave-length be referred to 3933.667. The measurements carried out on the absorption line K_3 reported in *Contribution* No. 48[1] point to a slightly shorter wave-length at the limb of the sun, where on the whole the effect of line-of-sight motion was probably eliminated; and, moreover, at the elevation at which the absorption line is produced, the pressure is probably less than one atmosphere, which is the value to which the arc wave-length is referred.

VERTICAL MOTION OF CALCIUM VAPOR OVER FLOCCULI

In Table III are assembled the results of the measurements of the wave-lengths of the K_2 and K_3 lines of calcium over the surrounding flocculi and outside the penumbral region of the spots. Points were taken on flocculi north, south, east, and west, and at different distances from the spots in order that the mean might fairly represent the average condition over the flocculi.

The division of the table into two parts was, as in the preceding one, for the purpose of using the two sets of measurements as checks upon each other. The K_2 line is very difficult to measure, because

[1] *Astrophysical Journal*, **32**, 36, 1910.

its components over the flocculi are very broad and each component is bounded differently on its two edges—on one edge by the K_1 shading and on the other by the K_3 line, and these boundaries are of different intensities. Moreover, the intensity of the K_2 component falls off more gradually toward the K_1 shading than toward

TABLE III

THE K_2 AND K_3 LINES OF CALCIUM OVER CENTRAL FLOCCULI

NUMBER	NORTH AND EAST		SOUTH AND WEST	
	K_2	K_3	K_2	K_3
6577	3933.677(2)	3933.679(2)	3933.680(2)	3933.696(2)
6602	.643(2)	.667(2)	.657(2)	.671(2)
6604	.648(3)	.682(2)	.673(2)	.676(1)
6606	.677(2)	.670(2)	.678(1)	.674(1)
6608	.656(2)	.665(2)	.678(2)	.682(2)
6609	.650(3)	.666(3)	.670(6)	.677(5)
6625	.675(3)	.685(3)	.663(3)	.683(3)
6627	.659(3)	.673(3)	.667(3)	.680(3)
6660	.683(2)	.689(2)	.689(2)	.688(2)
6695	.680(7)	.681(5)	.676(7)	.690(6)
6746	.670(4)	.685(4)	.661(4)	.677(4)
6753	.658(10)	.673(8)	.663(3)	.680(2)
6756	.657(4)	.688(4)	.664(6)	.680(6)
6765	.654(2)	.685(2)	.666(6)	.678(6)
6771	.660(2)	.678(2)	.644(2)	.659(2)
6772	.657(3)	.682(3)	.653(7)	.665(7)
6774	.633(2)	.660(2)	.646(2)	.679(2)
6786	.666(3)	.682(3)	.658(3)	.679(3)
6787	.651(5)	.684(5)	.651(5)	.678(5)
6788	.659(6)	.675(6)	.671(8)	.689(8)
6847	.684(2)	.695(2)	.672(2)	.684(2)
6849	.681(3)	.691(3)	.667(3)	.666(3)
6874	.677(2)	.676(2)	.673(2)	.667(2)
6880	.666(3)	.676(3)	.675(2)	.680(2)
6886	.663(3)	.679(3)	.666(2)	.683(2)
6897	.672(2)	.685(2)	.656(3)	.686(3)
	3933.663(85)	3933.679(80)	3933.665(90)	3933.679(86)

the K_3 line. The plates have been measured red right and red left, with from four to ten settings on each component in each position. It was found of advantage to use the adjustable slide over the plate to fix the portion of the line under measurement, and to eliminate as far as possible effects that might arise from the rapidly varying width of the bright component. In general these components appear to the eye to be of nearly equal widths over the flocculi.

The marked dissymmetry that is evident over the central portion of the disk outside of the flocculi shows but slightly, partly because the components are so broad, but mainly because it does not exist to the same degree. The mean wave-length for the two closely agreeing sets depending upon 175 measurements is 3933.664 Å against 3933.667 Å in the arc and 3933.641 Å at the center of the disk.[1] This indicates a small ascending movement of 0.23 km per second for the emitting vapor, against an upward velocity of 1.97 km per second for this vapor over the general solar surface. There are some indications in the measurements at different distances from the spot that the upward movement increases with increasing distance, but the number of measurements is not sufficient to fix this point. This result for the bright calcium over the flocculi is not in agreement with the general assumption that over the flocculi this vapor is rising rapidly from the interior of the sun or from a hotter lower stratum. The present investigation has been confined to the usual conditions in the flocculi and has not dealt with the exceptional eruptive phenomena. No measurements are known to the writer supporting the assumption of rapid upward motion, which seems to rest upon what appeared to be a very natural explanation of spectroheliographic data.

VERTICAL MOTION OF CALCIUM OVER CIRCUMFACULAR REGIONS

In the previous paper, "The General Circulation of Calcium Vapor," the measurements of the K_3 line were limited to regions free from spots and faculae. In the present investigation such measurements have been extended to the facular and circumfacular regions in order to detect any local circulation that might have its seat there, and to determine whether the facular and circumfacular regions are in any way complementary to each other. The measurements are given in Table IV and refer to the faculae surrounding the spots investigated, which were always near the center of the disk.

The mean of all the measurements is 3933.678, but omitting spots 6771, 6772, 6774, which appear to form a group by them-

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 48, 21, 1910; *Astrophysical Journal*, **32**, 56, 1910.

selves, the mean is 3933.680. The mean of 166 measurements of the wave-lengths of K_3 over faculae is 3933.679. In the paper "The General Circulation of the Calcium Vapor" already referred to, the wave-length of the K_3 line at the center of the sun was found to be 3933.680, and in the arc 3933.667. The agreement between the means of the three solar determinations is so close that it seems evident that the conditions obtaining in the case of the upper calcium layer of the solar atmosphere are the same over the general surface, the faculae, and the region immediately surrounding the faculae; and that a local system of circulation between the facular

TABLE IV

THE K_3 LINE OVER CIRCUMFACULAR REGIONS

Spot Number	Wave-Length	Spot Number	Wave-Length
6577	3933.681(1)	6765	3933.672(6)
6602	.676(5)	6771	.668(6)
6604	.684(4)	6772	.666(5)
6606	.683(4)	6774	.661(5)
6608	.687(4)	6786	.682(8)
6609	.686(9)	6787	.677(3)
6625	.684(6)	6788	.677(5)
6627	.678(7)	6847	.675(3)
6660	.685(3)	6849	.680(3)
6695	.673(10)	6874	.687(6)
6746	.681(4)	6880	.679(4)
6753	.676(5)	6886	.672(3)
6756	.681(5)	6897	.677(1)
Mean			3933.678(134)

and circumfacular regions is not the usual condition in the high-level vapor. Twenty-six circumfacular regions were investigated, twenty-three of which show a descending motion of the absorbing vapor at every point at which measurements were made. These points have been taken on all sides and at varying distances from the edges of the brilliant flocculi. In nine cases out of ten, therefore, the measurements indicate a descent of the high-level calcium vapor in the regions surrounding the faculae. In a tenth of the cases, namely in the circumfacular regions of spots 6771, 6772, and 6774, the mean of the measurements is 3933.665 Å. Compared with wave-length 3933.667 in the arc this would indicate a possible upward motion of 150 m per second; but the outstanding differ-

ence of 0.002 Å is too small to predicate motion upon, and moreover the low pressure at this high level might account for the slight difference, as the shift per atmosphere is only 0.002 Å. Reference was made above to the possibility that these three spots form a special group. They were on the disk at the same time; two of them, 6771 and 6772, crossed the central meridian at the same hour; spot 6772 crossed 0.7 day later. It is of interest in this connection to compare the entire set of measurements at their following apparitions as 6786, 6787, and 6788, and with the mean of the whole series of spots. These data are assembled in Table V.

TABLE V

COMPARISON OF SPECIAL SPOTS WITH WHOLE SERIES

Spot No.	Circumfaculae K_3	Faculae K_3	Penumbrae K_3	Umbrae Bright Line
6771.....	3933.668	3933.668	3933.673	3933.688
6772.....	.666	.670	.676	.666
6774.....	.661	.670	.678	.670
6786.....	.682	.685	.681	.697
6787.....	.677	.687	.681	.693
6788.....	.677	.676	.682	.684
Whole series..	.680	.679	.680	.682

It will be noticed that in the case of these three spots at their first apparition the state of the absorbing vapor was exceptional over the faculae as well as over the circumfacular regions, in neither instance showing any indications of a circulation between the two regions; and that in the case of two spots the calcium vapor was not descending over the umbrae, while on their second apparition all three were in agreement with the majority of the spots observed in showing a descent of the calcium.

The results of this investigation of twenty-six circumfacular regions appear to differ from those obtained by M. Deslandres as reported in the *Annales de l'Observatoire de Meudon*, Tome IV, pp. 75–79. Measurements were carried out at Meudon over the faculae and their immediate surroundings upon plates taken with the *spectro-enregistreur des vitesses*.

Les mesures ont porté seulement sur la raie centrale K_3, qui est nette et bien délimitée sur le disque entier; on a laissé de côté, au moins provisoirement,

la raie K_2, dont les composantes ne se prêtent pas toujours à un pointé précis. Les vitesses sont seulement relatives, car on a adopté pour déplacement zéro la moyenne des déplacements de tous les points de l'image. Or sur la facule, dans la grande majorité des cas, ... les vitesses sont descendantes, et tout autour ascendantes. Ce fait expérimental a été vérifié sur une dizaine des facules.

And again, page 93:

Cette conclusion, avant d'être acceptée comme absolument définitive, devra être appuyée sur des mesures plus nombreuses de vitesse radiale, faites non seulement au centre du Soleil, où les vitesses verticales seules interviennent, mais à une certaine distance de ce centre; ce qui permettrait de reconnaître les vitesses parallèles à la surface. Dès, à présent, on peut affirmer qu'elle est extrêmement probable.

The apparent disagreement in the results of the two investigations may possibly be referred to the different types of faculae studied in the two cases. In the present work all the faculae are large and in the immediate neighborhood of spots. The case shown in the Meudon *Annales* is that of a small facula unconnected with any spot. Then, too, the Meudon measurements are relative, the zero of displacement being the mean of all the displacements. In the present investigation the second slit was wide enough to admit the two iron standards, one on each side of K_3, from which the absolute wave-length of the displaced K_3 line was determined and through which the measurements were referred to the wave-length of the K line in the arc. From the adoption of the arbitrary zero in the former case it may be that the rise of the absorbing vapor in the circumfacular regions is only apparent, and that it is really descending in both regions, which would bring the results into nearer agreement. In view of the bearing of the results upon hypotheses relative to systems of circulation in the solar atmosphere the investigations at Mount Wilson will be extended to include large and small faculae and their immediate surroundings in cases where there are no associated spots.

RADIAL AND ROTATIONAL MOTION OF THE CALCIUM VAPOR OVER THE PENUMBRAE OF SPOTS

Radial movement of the reversing layer in sun-spots, showing an outflow with a velocity of one or two kilometers per second,

was announced by Evershed in 1909.[1] In a subsequent paper, under the heading "Radial Motion in the Higher Chromosphere,"[2] he writes as follows:

> I have said that the spectrum-lines are universally found to be displaced toward the red on the side of the penumbrae nearest the limb, and to the violet on the opposite side, thus indicating an outward movement. There are, however, two notable exceptions among the host of absorption lines in the solar spectrum. The central absorption lines, known as H_3 and K_3 (possibly also the underlying emission-lines H_2 and K_2) when clearly defined in the penumbrae, are displaced in exactly the opposite sense in every case I have examined, that is, towards the violet on the limb side of the spot, thus indicating an indraught of the calcium vapour of the higher chromosphere. . . . . It would seem natural to suppose that the calcium vapour is drawn downwards as well as inwards, and I cannot at present say whether this is so or not, although some of my measures indicate such a downdraught.

In the same paper Mr. Evershed considers the question of a spiral motion of the outflowing vapors of the reversing layer. He finds in the case of five spots a mean rotational movement of 0.35 km per second and a radial motion of about 2 km per second, by combining which he gets a spiral movement opposite in direction in the two hemispheres. In the present investigation of the movement of the chromospheric calcium vapor to which the origin of the lines K_2 and K_3 is referred, plates were taken in the case of four spots with the slit of the spectrograph across the centers of the umbrae and *parallel* to the radius of the solar image passing through the spot. The measurements were carried out upon both the K_2 and the K_3 lines over the limb edges and center edges of the penumbrae of the spot as shown in Table VI.

The typical appearance of the absorption line K_3 was that of a sinuous curve showing no abrupt change in direction at the outer limit of the penumbrae, but bending gradually back into the undisplaced line, as indicated by Plate V (*b*). Three of the four spots were followed from the east to the west limb; one was observed only near the east limb; but in every instance the wavelength on the edge of the penumbra toward the center was greater than on the edge toward the limb. In the former case the wave-

[1] Evershed, *Monthly Notices of the Royal Astronomical Society*, **69**, 454, 1909.

[2] *Ibid.*, **70**, 218, 1910.

length was longer than the corresponding wave-length in the arc, and in the latter the wave-length was always shorter than in the arc. The mean line-of-sight components for the four spots and the

TABLE VI

THE K_2 AND K_3 LINES OF CALCIUM OVER THE PENUMBRAE OF ECCENTRIC SPOTS

Slit parallel to the radius through the spot

SPOT	PLATE	DATE	LIMB EDGE		CENTER EDGE		REMARKS
			K_2	K_3	K_2	K_3	
		1910					
No. 6869 On C.M. July 18.6, 1910	173c	July 15	3933.650	.658	3933.673	.683	Line curved. 29 mm from East limb Return of 6862
No. 6874 On C.M. Aug. 9.5, 1910	182c	Aug. 4	.660	.637	.673	.668	Line curved. Spot 6 mm from East limb 1st apparition. Returned as 6880
	185c	Aug. 5	.653	.651	.702	.698	Line strongly curved. 17 mm from East limb
	187c	Aug. 6	.656	.651	.687	.690	Line curved. 30 mm from East limb
	195c	Aug. 9	.666	.661	.687	.687	On central meridian. 59 mm from South limb
	199c	Aug. 11	.664	.659	.662	.680	Line curved. 35 mm from West limb
	201c	Aug. 12	.651	.638	.680	.683	Line curved. 23 mm from West limb
			3933.658	.650	.680	.683	
No. 6880 On C.M. Sept. 5.8, 1910	219c	Aug. 31	.632	.637	.652	.669	Line sharply curved. 4 mm from East limb. Return of 6874
	221c	Sept. 1	.639	.639	.668	.668	Line curved. 12 mm from East limb
	223c	Sept. 8	.631	.624	.670	.686	Line strongly curved. 25 mm from West limb
	225c	Sept. 9	.633	.625	.681	.688	Line strongly curved. 15 mm from West limb
			3933.634	.631	.668	.678	
No. 6886 On C.M. Sept. 26.9, 1910	237c	Sept. 21	.645	.635	.665	.685	Line curved. 5 mm from East limb
	249c	Sept. 22	.649	.639	.686	.719	Line strongly curved. 13 mm from East limb
	255c	Sept. 24	.661	.654	.665	.693	Line curved. 40 mm from East limb
	256c	Sept. 26	.655	.653	.666	.687	
	261c	Oct. 1	.660	.640	.684	.702	Line curved. 8 mm from West limb
			3933.654	.644	.673	.697	

corresponding motions along the solar surface found by dividing by the sine of the angular distance from the center are given in Table VII.

This gives an average horizontal velocity of 2.0 km per second for the absorbing vapor and of 1.24 km per second for the emitting vapor on each side of the spot. For the absorbing vapor the mean result corresponds closely with the mean found by Mr. Evershed,

namely 1.83 km per second. The results for the K_2 line are of less weight owing to the greater uncertainties in the measurement; but it is an interesting fact that the mean is decidedly less than in the case of the absorbing vapor, that every measurement points

TABLE VII

LINE-OF-SIGHT COMPONENTS AND MOTIONS ALONG SOLAR SURFACE

SPOT NO.	UNREDUCED		REDUCED	
	K_2	K_3	K_2	K_3
6869	1.75 km	1.91 km	2.59 km	2.75 km
6874	1.68	2.59	2.29	3.51
6880	2.59	3.12	3.20	4.42
6886	1.45	4.04	1.83	5.33
Relative motion	1.87	2.91	2.48	4.00
On each side	0.94	1.46	1.24	2.00

in the same direction, and that a similar difference appears, as will be seen later, in the measurements when the slit was perpendicular to the radius of the solar image passing through the spot. The data for the seven spots on which observations were obtained with the slit *perpendicular* to the radius are given in Table VIII.

With a slit normal to the radius vector through the spot the radial flow of the vapor would produce no Doppler effect, but the rotational or spiral movement of the vapor would displace the line on one side of the spot to the red and on the opposite side to the violet. After the spot passes the meridian the displacements on the two edges of the spot would be reversed; if the direction of rotation is such that the north edge is approaching when the spot is east of the meridian the north edge will be receding when the spot is west of the meridian. This was distinctly the condition shown by spot 6577 and its return as 6592, and also by spot 6874. Of the seven spots observed, counting each apparition, five showed relative displacements of the K_2 and the K_3 lines for the north and south edges. On Plate V (*c*) is shown an enlarged reproduction of a limited portion of the spectrum of spot 6874 with the slit at right angles to the radius vector. On the original negative the displacements on the opposite sides of the spot are very distinctly

visible. By holding the reproduction on the level of the eye and looking along the line the relative displacements may be seen.

TABLE VIII

THE K_2 AND K_3 LINES OF CALCIUM OVER THE PENUMBRAE OF ECCENTRIC SPOTS

Slit perpendicular to the radius through the spot

SPOT	PLATE	DATE	I			II			REMARKS
			K_2	K_3	Edge	K_2	K_3	Edge	
		1908							
No. 6577	144	Dec. 13	3933.649	.639	N.	3933.711	.706	S.	At West limb. Returned as 6952
On C.M.									
Dec. 8.3,			.651	.648	N.	.706	.714	S.	
1908									
No. 6592	183	Dec. 30	.649	.635	S.	.677	.677	N.	At East limb. Return of 6577
On C.M.									
Jan. 4.7,			.659	.645	S.	.664	.666	N.	
1909									
			3933.652	.642		3933.690	.691		
		1909							
No. 6610	237	Jan. 28	.676	.683	N.	.686	.689	S.	8 mm from East limb
On C.M.			.670	.663	N.	.669	.683	S.	Only observation
Feb. 2.2,			.682	.676	N.	.680	.694	S.	
1910			.677	.671	N.	.684	.704	S.	
			3933.676	.673		3933.680	.693		
		1910							
No. 6869	173c	July 15	.664	.656	N.	.691	.683	S.	29 mm from East limb
On C.M.			.667	.660	N.	.681	.694	S.	Only observation
July 18.6,									
1910			3933.666	.658		3933.686	.689		
No. 6874	182c	Aug. 4	.668	.683	N.	.666	.650	S.	6 mm from East limb. Line curved. Returned as 6880
On C.M.									
Aug. 9.5,			.670	.685	N.	.671	.663	S.	
1910	185c	Aug. 5	.666	.683	N.	.661	.645	S.	17 mm from East limb. Line curved
	195c	Aug. 9	.676	.680	E.	.674	.672	W.	On central meridian 30 mm South of center
	199c	Aug. 11	.691	.692	S.	.664	.666	N.	35 mm from West Limb. Line curved
	210c	Aug. 14	.669	.672	S.	.652	.642	N.	5 mm from West limb. Line curved
			.672	.684	S.	.651	.638	N.	
			3933.673	.683		3933.663	.654		
No. 6880	219c	Aug. 31	.648	.652	N.	.659	.667	S.	4 mm from East limb. Return of 6874
On C.M.									
Sept. 5.8,	221c	Sept. 1	.656	.660	N.	.661	.661	S.	12 mm from East limb
1910	223c	Sept. 8	.681	.682	S.	.679	.681	N.	25 mm from West limb
			.671	.683	S.	.663	.667	N.	
			3933.666	.667		3933.664	.669		
No. 6886	237c	Sept. 21	.654	.666	N.	.663	.668	S.	5 mm from East limb
On C.M.	249c	Sept. 22	.673	.677	N.	.672	.679	S.	13 mm from East limb
Sept.26.9,	261c	Oct. 1	.684	.700	S.	.681	.686	N.	8 mm from West limb
1910									
			3933.670	.681		3933.672	.678		

In the case of spot 6577 when it was near the west limb the north edge of the penumbrae gave the shorter wave-length. When it appeared at the east limb as 6592 the south edge gave the shorter

wave-length. Considering the relative displacements at the two edges of the penumbrae as due to motions in the line of sight, it follows that when the spot was east of the meridian the penumbral calcium vapor was approaching on the south side and receding on the north side; and when the spot was west of the meridian the penumbral calcium vapor was approaching on the north side and receding on the south side—indicating in both instances a counter-clockwise rotation for this spot, which was situated in north latitude. In the case of spot 6874 observed during its passage from the east to the west limb, the rotation was in the same direction, but the

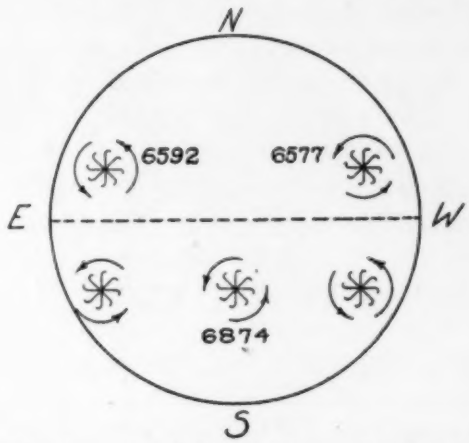


FIG. 1.—Spots in two hemispheres with same direction of rotation

spot was situated in south latitude. That these displacements are not due to an easterly and westerly drift on the north and south sides of the spot is shown by an observation on spot 6874 when on the meridian and south of the center by approximately one-third of the solar radius. In this position of the spot with the slit at right angles to the radius the displacements indicated approach of the penumbral vapor on the west side and recession on the east side, thus pointing to a true rotary movement. Of the three spots in the northern hemisphere two, 6610 and 6609, show a clockwise rotation; one, 6577, and its return, 6592, show a counter-clockwise rotation. We have then the two cases: spots in the same hemisphere showing opposite rotations and spots in the two hemi-

spheres showing rotation in the same direction. In reference to his own observations Mr. Evershed says:[1]

> The opposite movement in the two hemispheres, although clearly shown in five instances, may not be an invariable rule. Referring to the magnetic field in spots, Professor Hale states that "although the larger spots in the northern and southern hemispheres of the Sun are usually found to be of opposite polarity, it frequently happens that spots of opposite polarity occur in the same hemisphere, sometimes in the same spot group."[2] One would expect, therefore, if the rotation movement bears a causal relation to the magnetic field, to find occasional instances of spots showing a clockwise rotation in the north, or vice versa.

Two of the seven spots observed, 6880 and 6886, showed no evidence of rotational motion. One of the two, 6880, was the return of 6874, which on its first apparition showed such motion unmistakably. The means of the line-of-sight components of the rotational motion and the corresponding velocities along the solar surface found by dividing by the sine of the angular distance from the center are given in Table IX.

TABLE IX

LINE-OF-SIGHT COMPONENTS AND MOTIONS ALONG SOLAR SURFACE

SPOT NO.	UNREDUCED		REDUCED	
	K_2	K_3	K_2	K_3
6577	4.50 km	5.11 km	4.50 km	5.11 km
6592	1.30	2.36	1.45	2.59
6610	0.30	1.52	0.38	1.67
6869	1.52	2.36	2.29	3.58
6874	0.76	2.21	1.19	2.92
Relative motion	1.68	2.71	1.96	3.17
On each side	0.84	1.36	0.98	1.59

This gives an average horizontal rotational velocity of 1.59 km per second for the absorbing vapor and of 0.98 km per second for the emitting vapor on each side of the spot. The combination of the rotational movement with the inflow and downward movement gives a real vortical motion inward for the calcium vapor in the case of these four spots.

[1] Evershed, *Monthly Notices of the Royal Astronomical Society*, **70**, 224, 1910.

[2] Hale, *Publications of the Astronomical Society of the Pacific*, **21**, 205, 1909.

[*To be continued*]

A PRISM WITH CURVED FACES, FOR SPECTROGRAPH OR SPECTROSCOPE[1]

By CH. FÉRY

I

Spectrographs have almost entirely replaced spectroscopes in chemical investigations; they have the important advantage over the latter instruments of recording the results obtained. The use of the classic micrometer is rendered unnecessary by photographing upon the same plate the spectrum of iron, the lines of which have been carefully standardized. Measurements of the wave-length of the lines of the metal or of the body studied are then made with great precision by measuring the plate on a small dividing engine. Since the lines of iron are very numerous and very fine, it is easy to obtain by interpolation the wave-length of the unknown lines which are present with those of the standard spectrum. This apparatus is especially recommended for the blue, violet, and ultra-violet regions, these being the radiations for which ordinary photographic plates are sensitive. Also in these regions the dispersion of nearly all refracting substances is considerable, and the large scale of the resulting spectrum is very favorable to precision of measurement.

The region easily photographed lies between 6600 and 2200 Å.U. To get these last wave-lengths it is necessary to make use of quartz, which does not absorb them.

II

The spectrograph usually employed consists of one or two 60° prisms of quartz, placed at minimum deviation for the middle of the region to be photographed, and cut so that the general direction of the beam is parallel to the axis of the quartz. If a single prism is employed it must be made by the combination of two 30° prisms, one of right-handed, the other of left-handed quartz, the indices of the two for right- and left-handed circularly polarized light being slightly different (Cornu prism).

[1] Translated from the *Journal de Physique* (4) **9**, 762, 1910; with additional remarks and illustrations from the author.

To increase the scale of the spectrum, since quartz has a dispersive power which is only about a third of that of flint glass, lenses of long focus are used (of the order of 0.50 meter to one meter), these lenses being cut perpendicularly to the axis, from crystals of opposite rotation. Usually these lenses are not achromatic; fluorite and Iceland spar are practically the only two materials which it is possible to associate with quartz without increasing the absorption in the ultra-violet; but these substances are rare and expensive, and Iceland spar has also a pronounced double refraction, troublesome in this connection. On account of the lack of achromatism the focus of the ultra-violet rays is much shorter than that of the visible rays, and the photographic plate must make an acute angle with the rays issuing from the second lens. This angle, which we shall calculate in the case of a spectrograph with only one prism, is evidently independent of the focal length of the lenses.

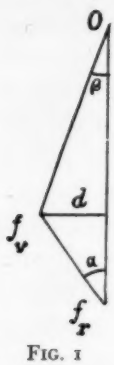


FIG. 1

Let O (Fig. 1) be the optical center of the combination of the two lenses between which the prism is placed, β the angle of dispersion between wave-lengths λ_v and λ_r, and f_v and f_r the focal lengths, violet and red, of the two radiations. We have

$$\frac{\tan\alpha}{\tan\beta}=\frac{\frac{d}{f_r-f_v}}{\frac{d}{f_v}}=\frac{f_v}{f_r-f_v}.$$

The difference in focal lengths, f_r-f_v, is easy to calculate for one of the lenses, by applying the known formula

$$\frac{1}{f_v}=(n_v-1)\Sigma\frac{1}{R},$$

$$\frac{1}{f_r}=(n_r-1)\Sigma\frac{1}{R}.$$

For the joint effect of the two lenses the difference will evidently be twice as great, and equation (1) will become

$$\frac{\tan\alpha}{\tan\beta}=\frac{f_v}{2(f_r-f_v)}.$$

If we take, for getting this ratio, the two extreme radiations, of which the ordinary indices are, for quartz,

$$\text{Line } A \ . \ . \ . \quad n_r = 1.539$$
$$\text{Line } P \ . \ . \ . \quad n_v = 1.568$$

we find

$$\frac{\tan \alpha}{\tan \beta} = 9.25 .$$

Let us calculate β.

$$n_r \sin \frac{A}{2} = \sin \frac{A+\delta_r}{2} ,$$

$$n_v \sin \frac{A}{2} = \sin \frac{A+\delta_v}{2} ,$$

or for quartz

$$1.539 \times 0.5 = \sin \frac{A+\delta_r}{2} = \sin 50°02 ,$$

$$1.568 \times 0.5 = \sin \frac{A+\delta_v}{2} = \sin 51°60 .$$

The difference $51°60 - 50°02 = 1°58$ represents then $\frac{1}{2}(\delta_v - \delta_r)$. The angle of dispersion of the 60° prism is therefore

$$\beta = 2 \times 1°58 = 3°16$$
$$\tan \beta = .056$$

and

$$\tan \alpha = .056 \times \frac{f_v}{2(f_r - f_v)} = .056 \times 9.25 = 0.508 ,$$

therefore

$$\alpha = 27° .$$

It is then at this small angle of 27°, or 63° with the normal to the plate, that the rays must meet the latter.

Moreover the foci of different colors are distributed on a curved surface, which makes it necessary to bend the plate or to employ films in order to get as near as possible to the form of the diacaustic. This large inclination of the photographic plate results in multiplying the dispersion by $\frac{1}{\sin 27°} = 2.2$, but it offers the disadvantage of multiplying by the same factor the width of the lines, due to incorrect focusing. This observation explains the instability of the adjustment of spectrographs and shows how their different

parts must be assembled in a rigid manner if one wishes to obtain a stable adjustment.

We may add to these some other criticisms arising from the cumbrousness and the high price of these instruments, and also from the loss of light caused by the passage of the rays in the different media. Finally, the adjustment of this apparatus, although well known, is nevertheless secured only by a long and delicate operation, and can be accomplished only by trial, in so far as the inclination of the plate is concerned, as well as the curvature which must be given to it.

III

In trying to avoid these different objections I have put together a spectrograph, based upon the employment of a prism with curved faces, especially constructed, of which I shall give a description.

It is admitted that to obtain a pure spectrum it is necessary to cause a bundle of parallel rays to fall on the face of a prism placed at minimum deviation. The source is a slit as narrow as possible, set parallel to the refracting edge, and placed at the principal focus of the collimating lens. A second lens, receiving the different parallel monochromatic bundles, gives in its focal plane a clear-cut image of the slit.

One may say, in a very general way, that to get a pure spectrum it is necessary and sufficient that the angles of incidence of the different rays be equal. The same should be true for the angles of emergence, for all the rays of the same wave-length. This condition is evidently fulfilled by the prism with the plane faces such as is usually employed, but one may imagine other solutions which satisfy this condition equally well, and which realize also those of minimum deviation, and of equality of the angles of incidence and emergence.

Let R be the radius of curvature of the front face of the prism $MPQN$ (Fig. 2). Draw the lines PC and QC making with the normals at the points of incidence the equal angles i. The slit is placed at the point of intersection, C, of these two lines. The condition mentioned will be fulfilled by all the rays issuing from C and falling on the prism.

Let us imagine that the monochromatic radiation chosen is such that we have

$$\sin i = n_\lambda \sin r.$$

An angle r will then correspond to the angle of incidence i, and on prolonging the two rays thus refracted at P and Q, we shall obtain at their point of intersection, B, the center of curvature of the second surface MN of a prism with curved faces. This second surface is silvered to increase its reflecting power, and the refracted

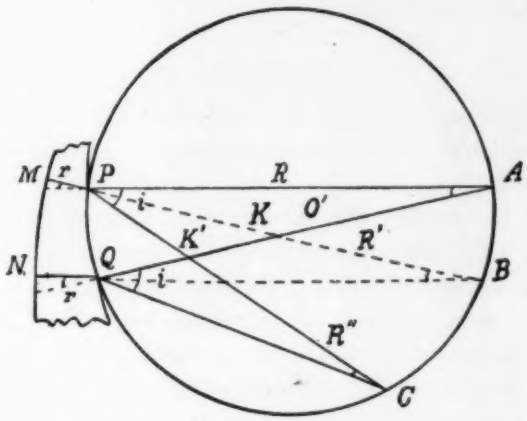


FIG. 2

rays, after all being reflected normally, will return to an exact focus on the slit itself.

If the radiation chosen were heterogeneous, the angles of refraction would be different for each color, but equal over the whole surface of the prism for any one color. After reflection from the surface MN the different rays of each monchromatic bundle would leave the prism with the same angle of refraction and would pass to an exact focus in the neighborhood of the slit.

It is easy to see from the figure that the angles A, B, and C are equal, for the two triangles which have for a common vertex the point K', where the lines PC and QA intersect, and as other vertices, the points P, A, C, and Q, are similar. They have an opposite angle at K' and two angles equal to i by construction. Therefore the angle at A is equal to the angle at C. In the same

way it may be shown that the angle at A is equal to the angle at B, and also that all monochromatic bundles which are concentrated in the neighborhood of C converge at this same angle.

A circle may therefore be passed through the points P, Q, C, B, and A.

The result is that the slit, the spectrum, and the centers of curvature of the two surfaces of the prism are upon the same circle, drawn with the radius of the first surface as a diameter. Since the distance PQ is small with respect to the distances R, R', and R'', we have obviously

$$R' = R \cos r$$
$$R'' = R \cos i,$$

relations which make it possible to calculate the radii of curvature and the focal length of the prism, knowing its angle r and its index $n \sin r = \sin i$.

In order to simplify the mounting of the apparatus an angle of incidence i is chosen larger than that producing normal reflection at the silvered surface. To the angle of incidence $i+di$ there corresponds an angle of refraction $r+dr$, and all the rays of each monochromatic bundle are reflected from the face MN, undergoing a deviation of $180^\circ - 2\,dr$; they all emerge at the same angle $i-di$, and converge to an exact focus upon the circle passing through the center of curvature of the two spherical faces of the prism.

It is easy to see, too, that the length of spectrum obtained is independent of the position of the spectrum on the circle.

This length is equal to δ (the angle between the extreme rays of the spectrum), multiplied by the distance of the prism from the photographic plate, and divided by the cosine of the angle at which the rays strike the photographic plate at VR (Fig. 3).

$$l = \frac{\delta \times PR}{\cos i},$$

but

$$PR = R' \cos i.$$

Therefore the length of the spectrum photographed is

$$l = \frac{\delta \times R' \cos i}{\cos i} = \delta R' = \text{Const.}$$

Astigmatism of the system.—The conjugate focus of a point on the slit obtained by a narrow bundle parallel to the edge of the prism is evidently not the same as that calculated above. This results in a certain amount of astigmatism, as in the concave grating of Rowland.

There are various consequences of this astigmatism.

It renders the employment of comparison spectra more difficult. I have overcome the difficulty by limiting the spectrum with a screen, movable vertically, and pierced by a horizontal opening.

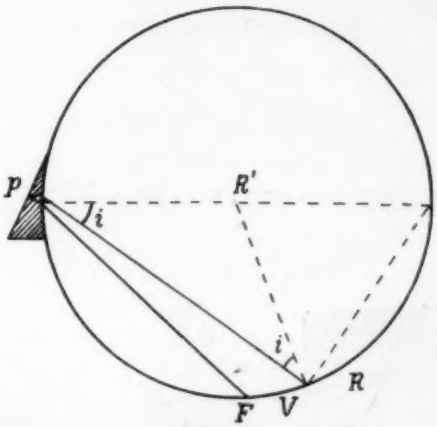


FIG. 3

By displacing this screen by an amount equal to the width of the opening which it carries, we may place upon the same plate the comparison spectrum, and this without changing the position of the image on the slit. The image of a point falling on the slit furnishes in fact a spectrum of lines.

The astigmatism presents, on the other hand, the advantage of not focusing the dust specks on the slit, and thus producing the disagreeable horizontal lines.

A spectrograph has been built embodying the foregoing principles. It is not cumbersome. The base is a casting which carries the slit, prism, and plate-holder, and may be covered by a case to prevent the entrance of dust into the apparatus, and to exclude outside light during an exposure.

The focus chosen is one meter, which corresponds for the quartz (a prism of 30°) to the same length of spectrum which would be given by lenses of 80 cm focal length and a prism of 60°. In reality the dispersion is even greater and the scale would corre-

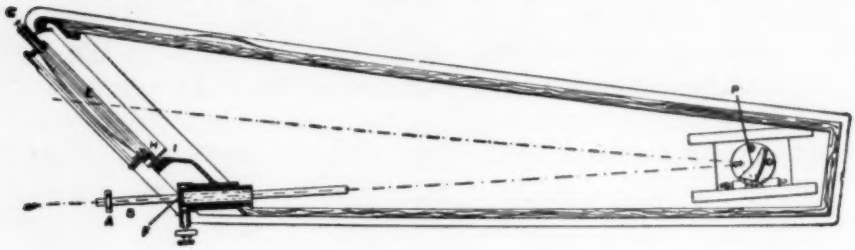


FIG. 4

spond to that of a spectrograph having the lenses of one meter focal length, but in the last-named instrument, as we have seen, the inclination of the plate to the beam of light is 27°. Here it is 39°, or 51° to the normal.

FIG. 5

The ordinary spectograph multiplies the dispersion, then, by

$$\frac{1}{\sin 27^\circ} = 2.2.$$

Here it is multiplied by only

$$\frac{1}{\sin 39^\circ} = 1.59.$$

The spectra given by the apparatus are about 220 millimeters long. The definition is very good throughout the whole extent of the plates used (24 centimeters in length).

IV

Application of this prism to the construction of a spectroscope. —It is sufficient to replace the plate-holder by a slide provided with a vernier and an eyepiece. The visible spectrum is about 9 cm long with a flint prism of one meter focal length. A vernier reading to $\frac{1}{20}$ mm therefore makes it possible to measure wave-lengths to one Ångström.

Eight instruments of this system have actually been constructed. One is employed at the Mint in Paris for testing alloys of gold and of silver. Another serves for the analysis of minerals containing radium. A third has been bought for studying the sources of the ultra-violet radiations utilized for the sterilization of water.

ÉCOLE MUNICIPALE DE PHYSIQUE ET DE CHIMIE
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